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DEVELOPMENT OF TITANIUM ALLOYS FOR CAST GAS TURBINE ENGINE COMPONENTS

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DETROIT DIESEL ALLISON DIVISION

GENERAL MOTORS CORPORATION

TECHNICAL REPORT AFML-TR-71-47

JULY 1971

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13. ABSTRACT

A two phase problem definition program was conducted to determine the need for development of titanium alloys for casting high speed rotating components, e.g., compressor impellers. (U)

Four commercially available alloys, Ti-6Al-4V, 5621S, IMI700 and Beta III were appraised with respect to castability and end-item casting performance potential. Phase I screening studies involved casting a stylized shape in refractory metal face coated ceramic shell molds by skull melting and bottom pour induction melting. Castings were subjected to non-destructive inspection, and after appropriate heat treatment, to tensile, high cycle reverse bending fatigue, ballistic impact and metallographic tests. On the basis of tensile and fatigue test data, Ti-6Al-4V alloy was considered the optimum alloy for high speed rotating component application. This alloy was further evaluated in Phase II via low cycle fatigue tests of skull melted stylized castings. In addition, tensile properties and destructive spin test behavior were determined for skull melted compressor impeller castings of T63 engine configuration. Ceramic molds were instrumented in an attempt to correlate cooling curves with microstructure and mechanical properties. It was concluded that castability of the alloys evaluated is essentially identical, and that there is no apparent need to develop new alloys for the purpose of producing complex titanium castings for visualized high speed rotating component applications. (U)

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DEVELOPMENT OF TITANIUM ALLOYS

FOR CAST GAS TURBINE ENGINE COMPONENTS

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FOREWORD

This report was prepared by Detroit Diesel Allison Division, General Motors Corporation, P.O. Box 894, Indianapolis, Indiana under USAF Contract No. F33615-69-C-1608. The contract was initiated under Project No. 7351, "Metallic Materials", Task No. 735105, "High Strength Metals". The work was administered under the direction of the Metals and Ceramics Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. Mr. Paul L. Hendricks (LLP) was Project Engineer.

This report covers work conducted during the period of 15 June 1969 through 14 January 1971. It was submitted for approval on 15 February 1971 as Detroit Diesel Allison Division Report EDR 7035. Mr. G. L. Vonnegut was the program manager and Mr. U. L. Hellmann was the principal investigator. Mr. T. C. Tsareff, of Detroit Diesel Allison Division Materials Engineering, was the major contributor to the program. Mr. N. H. Marshall, of REM Metals Corporation, Mr. T. S. Piwonka, of TRW Metals Division, and Mr. C. L. Smith, of Detroit Diesel Allison Division, also were contributors.

This technical report has been reviewed and is approved.

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ABSTRACT

A two phase problem definition program was conducted to determine the need for development of titanium alloys for casting high speed rotating components, e.g., compressor impellers.

Four commercially available alloys, Ti-6Al-4V, 5621S, IMI700 and Beta III were appraised with respect to castability and end-item casting performance potential. Phase I screening studies involved casting a stylized shape in refractory metal face coated ceramic shell molds by skull melting and bottom pour induction melting. Castings were subjected to non destructive inspection, and after appropriate heat treatment, to tensile, high cycle reverse bending fatigue, ballistic impact and metallographic tests. On the basis of tensile and fatigue test data, Ti-6Al-4V alloy was considered the optimum alloy for high speed rotating component application. This alloy was further evaluated in Phase II via low cycle fatigue tests of skull melted stylized castings. In addition, tensile properties and destructive spin test behavior were determined for skull melted compressor impeller castings of T63 engine configuration. Ceramic molds were instrumented in an attempt to correlate cooling curves with microstructure and mechanical properties. It was concluded that castability of the alloys evaluated is essentially identical, and that there is no apparent need to develop new alloys for the purpose of producing complex titanium castings for visualized high speed rotating component applications.

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SECTION I

INTRODUCTION

The systematic use of any new material produced into usable forms for gas turbine engine components requires a specific path of development and analysis to ensure functional integrity.

A major problem which largely prevented use of titanium castings was mold reaction with the liquid titanium alloy. Development of a shell molding method incorporating refractory metal impregnated mold surfaces has been accomplished. Thus, attention can now be directed toward determining the capabilities of the precision investment casting process to make complex shapes to finished dimensions, the suitability of specific alloys for such castings, and the merits of various melting practices. The overall goals of an alloy development program are to provide titanium casting alloys matched to specific casting processes for a broad spectrum of sizes and structural requirements - all with "satisfactory" surface finish and minimum weld repair needs. The overriding principle is the development of a competitively priced system satisfying the range of structural needs.

This problem definition program was conducted to determine the need for new alloy development by first appraising the suitability of presently available titanium alloys, with respect to castability and end-item casting performance potential, for application to complex gas turbine engine components. Emphasis was placed on requirements of high speed rotating elements, e.g., centrifugal impeller, with thin high aspect ratio elements.

The alloy and end-item casting goals were:

- Castability that permits the filling of web sections with aspect ratios of $\sim$ 20:1 when abutted to a massive primary section.
- Static strength of 130 ksi ultimate (normalized to the density of Ti-6Al-4V) with an elongation of 10% and a reduction of area of 10%.
- Freedom from internal shrinkage, laps, and hot tears when matched to specific casting and molding practices. Specifically, radiographic quality at least equal to ASTM E192, Grade 3 in thin sections.

This report describes work performed during the contract. It includes a description of the experimental procedures, a discussion of the results, conclusions, and recommendations.

SECTION II

EXPERIMENTAL PROGRAM

The program was divided into two phases: I - Commercial Alloy Screening and Property Evaluation; and II - Optimum Alloy Evaluation. The basic test plan is shown in Table I.

2.1 PHASE I - COMMERCIAL ALLOY SCREENING AND PROPERTY EVALUATION

2.1.1 Commercial Alloy for Study

The four commercially available heat treatable titanium alloys, normally used as wrought products, selected for initial studies to determine their characteristics as casting alloys are listed in Table II.

Table II

Characteristics of Selected Titanium Alloys

Alloy	Structure	Strength at temperature	
		Ambient	Elevated
Ti-6Al-4V	$\alpha + \beta$	Medium	Low
IMI700	$\alpha + \beta$	High	Medium
5621S	$\alpha + \beta$	Medium	High
B120VCA	β	High	Low

These alloys represented a wide range of compositions, as well as a wide range of strength capabilities from ambient to elevated temperatures up to 700F.

Early in Phase I, alloys IMI700 and B120VCA were replaced with Beta III alloy. Newly published data indicated that Beta III had higher potential than the replaced alloys with regard to achieving the program goals.

The alloys were purchased from the following vendors:

Ti-6Al-4V: Harvey Aluminum - Heat No. 32142486
Ti-6Al-4V[a]: Titanium Metals Corp.- Heat K2322
5621S: Reactive Metals Inc. - Heat No. 29420
5621S[a]: Oregon Metallurgical Corp. - Heat No. 5174-D1
IMI700: C. Tennant Sons and Co. - Heat No. A7454
B120VCA: Titanium Metals Corp. - Heat No. K2481
Beta III: Colt Industries Crucible Inc.: Heat No. K504[illegible]1

(a) These heats were required to complete the program following Phase I mid-course redirection.

Table I

Basic Test Plan

Phase	Alloy	Tensile tests Thick R.T.	Tensile tests Thick 700F	Tensile tests Thin R.T.	Vibratory fatigue tests	Ballistic impact tests	Low cycle fatigue tests R.T.	Low cycle fatigue tests 700F	Spin test
I	Ti-6Al-4V	4	4	6	4	2	---	---	---
	5621S	4	4	6	4	2	---	---	---
	IMI700 (a)	4	4	6	4	2	---	---	---
	B120VCA (a)	4	4	6	4	2	---	---	---
	Beta III (b)	4	4	6	4	2	---	---	---
II	Best (c)	6	---	---	---	---	---	---	1
	Best	---	---	---	---	---	7	7	---

(a) Eliminated from program per redirection.
(b) Added to program per redirection.
(c) Impeller casting.

2.1.2 Test Casting Configuration

A stylized casting configuration, shown in Figure 1, was designed to (1) provide specimens for metallographic evaluation and mechanical property tests, (2) obtain comparative evaluations of alloy castability, and (3) determine effects of casting practice and thermal treatments on casting dimensions. The structure and properties of this universal shape were expected to closely represent those in critical sections of various turbine engine components, e.g., a compressor impeller web (heavy section) and vanes (thin section) as well as a compressor vane airfoil (thin section).

The wax pattern die for the stylized specimen, built by Detroit Diesel Allison Experimental Manufacturing, contained inserts which permitted fabrication of patterns with thin section thickness of either 0.060 or 0.080 in. Originally the design did not incorporate a taper in the thickness direction of the thin test sections, but, as described in Section III, the taper was later required to enhance thin section quality.

2.1.3 Instrumentation

Test casting molds were instrumented with thermocouples to permit evaluation of the interrelationships between cooling rate, mechanical properties, grain size and other microstructural features. The temperatures of both the shell mold and the actual casting, in both the thick and thin sections, were monitored on a limited number of castings to establish a correlation. It was intended that once the correlation between shell and cavity had been established, only the shell mold would be instrumented. A mold instrumentation schematic is shown in Figure 2. Ta sheathed W-W/Re thermocouples were used in the cavity and bare W-W/Re couples in the shell. The cavity thermocouples were installed just prior to casting. Thermocouple outputs were recorded by high speed oscillographic devices.

A preliminary test of a 0.014-in. dia. Ta sheathed W-W/Re thermocouple, in contact with molten Ti alloy during casting and alloy solidification, was conducted to determine test efficiency and thermocouple life. A thermocouple was inserted into the cavity of a graphite mold and exposed to a molten charge of Ti-6Al-4V alloy. The thermocuple output was recorded

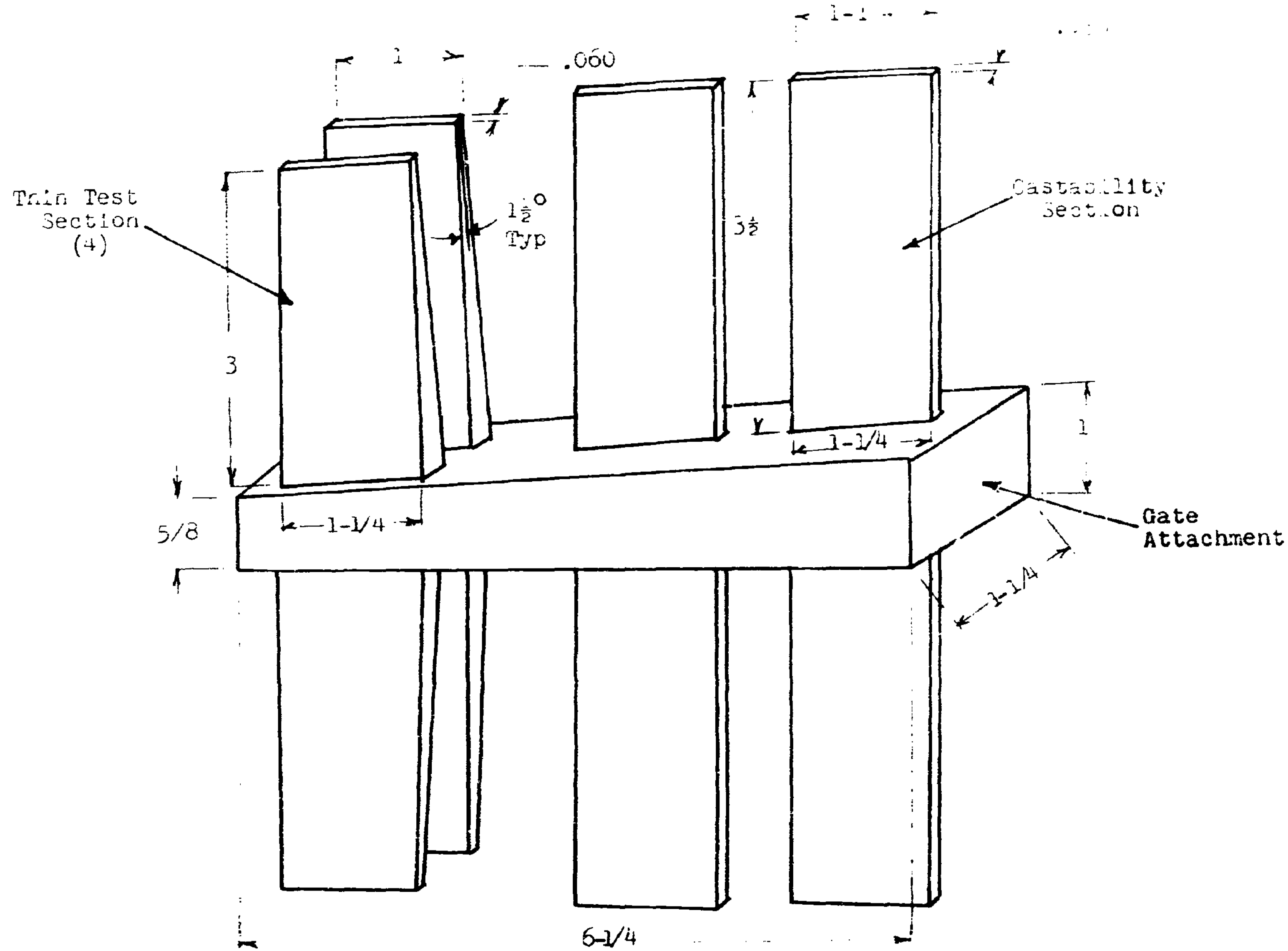
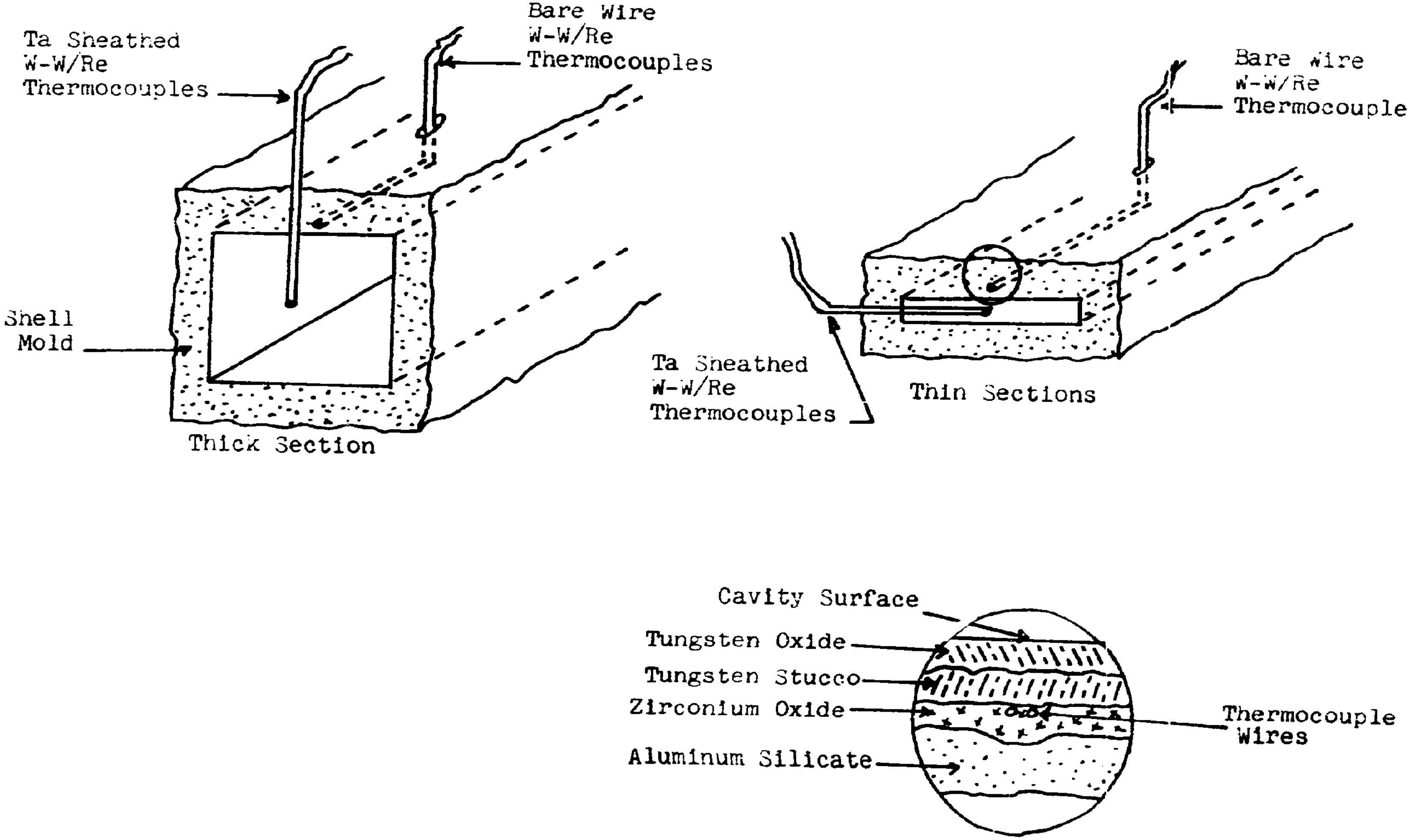


Figure 1. Stylized casting configuration.



Cavity thermocouples protruded into the cavity a minimum of 10 diameters of the sheath.

Shell thermocouples were attached to the tungsten stucco coating for a minimum length of 10 diameters of the wire.

Figure 2. Schematic for instrumenting stylized titanium casting.

on a fast response X-Y recorder, using parameters of time versus temperature. Sectioning of the ingot and resultant microexamination of the thermocouple sheath revealed only minor surface effects due to alloy diffusion. Thermocouple integrity was inviolate and considered satisfactory for recording of solidification curves. W-W/Re bare wire was encapsulated in a trial mold and exposed to a 3000F temperature in a laboratory furnace. Results of this test indicated accurate recording of shell temperatures and it was thus concluded that an unshielded thermocouple could be employed satisfactorily.

2.1.4 Melting and Casting Processes

Both induction and consumable electrode skull melting procedures were used at the start of the program. A review of early Phase I castability data indicated that the program goals could best be achieved by skull melting alone. At that point, induction melting was eliminated from the program.

2.1.4.1 Induction Melting

The induction melting practice used by TRW Metals Div. can be described with the aid of Figure 3. A specially designed induction coil is placed around an expendable crucible as shown. The bottom of the crucible contains a titanium alloy plug of the same composition as the main charge. The metal charge is mechanically suspended and does not contact the graphite crucible wall until completely molten and then for only a few seconds. A specially programmed power application is used to heat the entire charge to within a few degrees of the melting temperature. Power is then increased substantially to cause total melting within a few seconds. Almost immediately thereafter, the bottom plug melts and the molten charge is automatically tapped through the bottom of the crucible. The degree of superheat obtained is determined by the size of the metal plug used. Reproducibility of the pouring temperature is excellent, typically $\pm$ 10F. Melting and pouring rates are also remarkably reproducible. A vacuum of 10 microns or less is maintained throughout the melting-pouring cycle. The chamber is back filled with dry argon about 2 minutes after pouring to reduce total cycle time.

Ti-6Al-4V alloy castings melted by this method and poured in graphitized ceramic molds have consistently conformed to AMS 4928 composition requirements,

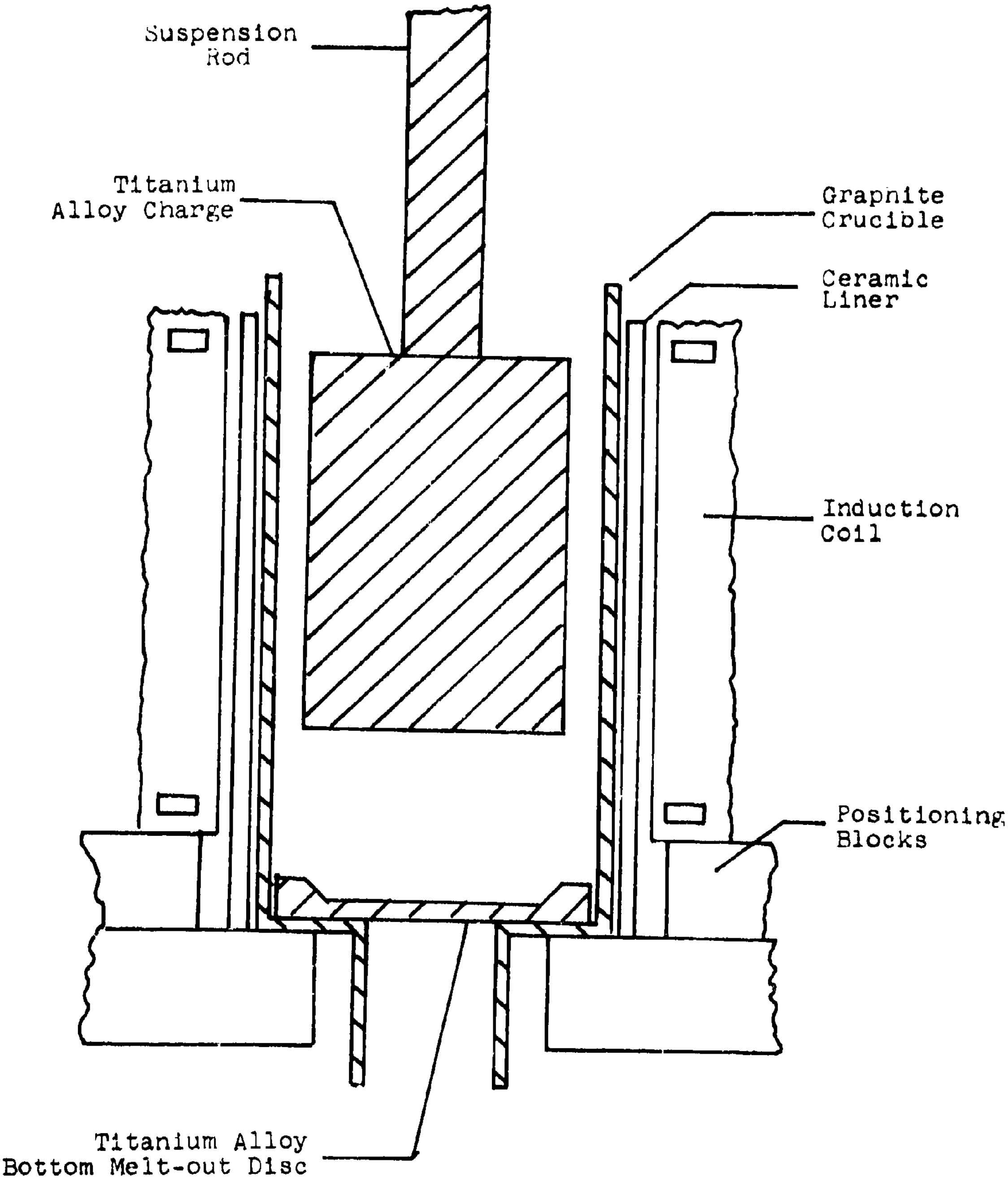


Figure 3. Schematic of induction melting process used by TRW Metals Division for titanium alloy casting.

provided that carbon content of the ingot was suitably low, e.g. <0.05%.

The induction process provides molten metal at controlled superheat from very rapid induction melting cycles which are short enough to prevent significant contamination of molten titanium by the relatively inert graphite crucible. For example, it is possible to melt and pour an eight pound charge of titanium in approximately four minutes. Of this four minute time, the charge is molten less than one minute. The very fast melting cycle, combined with levitation effects on the charge, produces molten titanium of aircraft quality.

2.1.4.2 Skull Melting

The skull melting process, used by REM Metals Corporation, is accomplished in a consumable electrode furnace. The chamber contains a sodium-potassium cooled copper crucible in which melting is accomplished. The melting stock is a large electrode. An arc is struck between the tip of the electrode and the copper crucible, thereby causing titanium to melt from the tip of the electrode and to form a molten puddle in the crucible. Since the crucible is cooled, titanium immediately in contact with the crucible walls freezes forming a "skull". In effect then, the molten material is contained within a crucible of itself or of the same alloy composition. This eliminates the possibility of contamination. When an adequate amount of metal has been melted to fill the mold, the power is turned off, the electrode retracted from the crucible, and the crucible turned to pour the metal into the mold. Usually 85% of the metal is poured and 15% is retained as "skull". A vacuum of 10 microns or less is maintained throughout the melting-pouring cycle. Molds are held in the vacuum after pouring until the temperature drops to approximately 400F. Titanium alloy electrodes are purchased from commercial alloy suppliers as double vacuum melted forging stock. Thus, the casting contains triple vacuum melted alloy.

2.1.4.3 Molding, Insulation, Preheating, and Clean-up

Uninsulated, tungsten metal face coated ceramic shell molds, of the same formulation and thickness were used throughout. All were prepared by REM Metals Corp.[1, 2]

A mold preheat temperature of 700F was used to pour skull melt stylized castings. This temperature was established during a General Motors funded precontract program as suitable for achieving ASTM E192 Grade 3 radiographic quality in thin sections of Ti-6Al-4V castings. Grade 3 is commensurate with Detroit Diesel Allison requirements for the steel version of the impeller component. These parameters were then used as the base line parameters for the other alloys so as to have a direct comparison for castability. A higher preheat temperature, determined by experimentation, was required to avoid severe misrun of thin sections in castings poured by the induction melting practice.

All casting knock-out and clean-up operations were preformed by REM Metals Corp. Clean-up consisted of grit blasting with garnet sand followed by immersion in a hot caustic salt bath (Kolene, DGS).

2.1.5 Screening Tests

2.1.5.1 Castability

The castability of the selected alloys was determined by adjusting the high aspect ratio castability sections of the stylized casting so as to produce incomplete filling by the base line alloy Ti-6Al-4V. The other alloys were then cast into the stylized configuration under the same casting parameters. The degree of fill and general quality of the castings was then used as an index of the individual alloy's castability. Radiographic, fluorescent penetrant and visual inspection techniques were used to determine the quality of the castings.

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(1) U.S. Patent No. 3,422,880: Method of Making Investment Shell Molds for the High Integrity Precision Casting of Reactive and Refractory Metals (REM Metals Corporation).

(2) U.S. Patent No. 3,537,949: Investment Shell Molds for the High Integrity Precision Casting of Reactive and Refractory Metals and Methods for their Manufacture (REM Metals Corporation).

2.1.5.2 Dimensional Stability

It was intended and would have been desirable to measure dimensional effects of heat treating on the thin test sections. However, the need to obtain flat specimens for mechanical tests resulted in a decision to remove the thin sections from the heavy sections prior to heat treatment. One whole casting was solution treated and aged. Measurements before and after heat treatment showed no distortional effect of the heat treatment. Thus, dimensional inspection of stylized castings was deleted.

2.1.5.3 Tensile Tests

Room temperature tensile properties were determined for thin and thick sections of the castings. The thin section specimens were flat samples while standard 0.252 in. diameter specimens were generated from the thick sections. A minimum of six thin section and four thick section tensile tests were conducted on each alloy-casting vendor combination. Measured values were ultimate strength, 0.2% yield strength, proportional limit, % elongation, % reduction of area and elastic modulus.

Elevated temperature tensile tests were performed at 700F on thick sections of the castings, using four specimens for each alloy-casting vendor combination.

Both room and elevated temperature test specimens from thick sections were run using a Riehle 60,000 lb. capacity unit with a strain rate of 0.005 in/in/min to the yield point. Strain was then increased to approximately 0.10 in/in/min, producing failure in less than 1 minute. Extensometers were used for strain measurement.

Thin section tests were conducted using an Instron 10,000 lb. capacity unit with a strain rate of $\approx$ 0.020 in/in/min from start to failure. An Istron extensometer with a 0.5 in. gage section was used for strain measurement. Flat 0.250 in. width by 0.05-0.06 in. thick by 1.125 in. length reduced section specimens were used.

2.1.5.4 High Cycle Fatigue

Thin sections of the castings were evaluated for room temperature high cycle fatigue properties by vibrating cantilever beam specimens in the fundamental bending mode by means of an air blast directed axially at the free end of the beam. Strain gages were used to monitor maximum bending strains which were correlated to tip amplitude measured by a calibrated telescope. The incremental step fatigue test procedure was used to determine the 5×10^6 cycle fatigue strength in reversed bending for each specimen. This involved vibrating the specimen at its resonant frequency at an initial stress level estimated to be half of the fatigue endurance limit stress and increasing the stress level by 10% of the estimated endurance limit stress on each succeeding step. The criterion for failure was established as either a visible crack, which generally resulted in total fracture, or a rapid decrease in fundamental frequency.

The endurance limit was determined by adjusting the failure strain by the following relationship:

Adjusted failure strain $= E_n + K\,(\Delta e)$

E_n = strain level of preceding step, in/in.

$\Delta e = E_f - E_n$

E_f = strain level at failure, in/in.

K = correction factor calculated from the following relationship

$$\text{Cycle ratio} = \frac{\text{number of cycles to failure on final step level}}{\text{endurance limit cycles } (5 \times 10^6)}$$

Cycle ratio	K
0 - 5%	5%
6 - 20%	20%
21 - 50%	50%
51 -100%	80%

The adjusted 5×10^6 cycle endurance limit was obtained by multiplying the adjusted failure strain by the modulus of the material.

2.1.5.5 Ballistic Impact

The relative foreign object damage resistance of the thin sections of the castings was evaluated by ballistic impact testing. Spherical steel pellets, 0.177 in. diameter were impacted normal to surface of specimens supported on both ends. The relative damage caused by impact velocities up to 755 feet/second (7 ft-lb) was measured by the amount of cracking produced and compared to wrought Ti-6Al-4V material at the same thickness.

2.1.5.6 Microstructure

General metallographic examination was made of the thin and thick sections to correlate grain size and phase distribution with mechanical properties and/or solidification rate. In addition, surface contamination, due to the casting process, was evaluated on thin and thick as-cast material by electron microprobe analysis.

2.2 PHASE II - OPTIMUM ALLOY EVALUATION

2.2.1 Low Cycle Fatigue Tests

The results of the screening tests were reviewed to determine the ranking of the alloys produced by the REM casting process. Ti-6Al-4V was selected as the alloy with the best overall combination of castability, quality and mechanical properties and was cast into ten (10) additional stylized test samples for low cycle fatigue testing. Isothermal, strain controlled low cycle fatigue tests were conducted at room temperature and 700F on specimens removed from the thick section of the test castings. Seven specimens were tested at each test temperature in order to establish strain range vs cycles to failure relationships. Plots of plastic, elastic and total strain range as a function of cycles to failure were generated for lives between 1 and 10,000 cycles.

2.2.2 Component Casting Evaluation

The alloy selected for low cycle fatigue evaluation was also cast into the T63 impeller configuration, using the optimum casting process. Two impeller castings were made. A photograph of the subject impeller is shown in Figure 4. This part is typical of complex configurations of highly stressed dynamic components which will benefit technically and cost-wise, when produced from lightweight, high-strength corrosion resistant titanium alloy casting.

Radiographic, fluorescent penetrant, and visual inspections were performed on the as-cast impeller castings and again after heat treatment.

One impeller casting was sectioned for tensile properties and microexamination. Room temperature tensile tests were conducted on the heat treated castings for comparison with the screening test results. Metallographic studies for surface

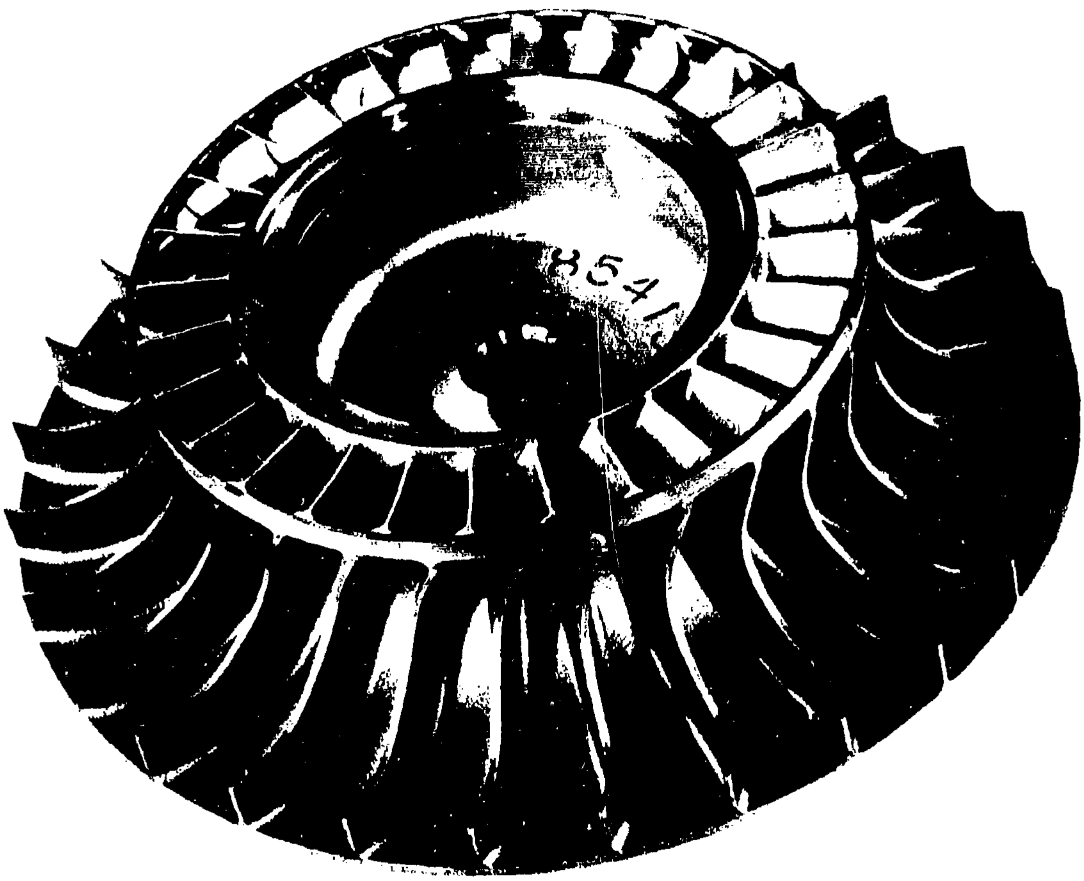


Figure 4. T53 impeller casting (Magn 1X) Neg. No. 8-25068

contamination, general quality, grain size, and microstructural characteristics were made on the heat treated casting.

The second impeller casting was spin tested to destruction at room temperature and failure analysis was performed to determine mode of failure.

SECTION III

RESULTS AND DISCUSSION

3.1 PHASE I - COMMERCIAL ALLOY SCREENING AND PROPERTY EVALUATION

3.1.1 Castability

Castability, as determined by visual and radiographic examination, of the stylized specimen cast in the program is summarized in Table III.

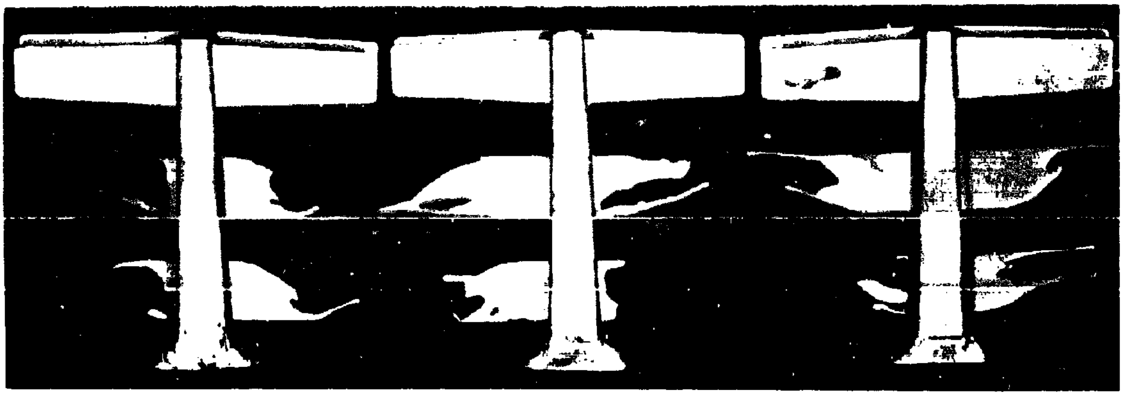
3.1.1.1 Visual Evaluation

Based on the visual appearance of the castability sections and the thin test sections, there was no apparent difference in the castability of Ti-6Al-4V, 5621S, IMI700, and Beta III alloys when cast by either the skull or induction melting processes.

Representative skull melt castings of nontapered thin test section configuration from REM are shown in Figure 5. The same variability in degrees of fill of the 0.035 in. castability sections was noted both between castings of the same alloy and between casting of different alloys. This was also true for specimens cast with the tapered thin test sections.

Representative induction melt castings of nontapered thin test section specimens from TRW are shown in Figure 6. Again the degree of fill of the castability sections did not appear to be alloy sensitive.

The data of Table III indicate that skull melting was more successful than induction melting with respect to producing sound thin test sections. A possible explanation for the inability to consistently fill the mold when using the TRW bottom pour induction melting process is that the coldest portion of the melt (the last of the charge to melt) enters the mold first and is solidifying before completely filling the cavities. One casting with 0.060 in. thin sections was poured at TRW using a very high 1500F mold preheat temperature. Two coats of the prime dip were employed on this mold in order to prevent penetration of titanium to the ceramic backup shell. Again, the thin test sections did not fill completely. Therefore, additional castings from TRW used the 0.080 in. instead of 0.060 in. thin test sections.



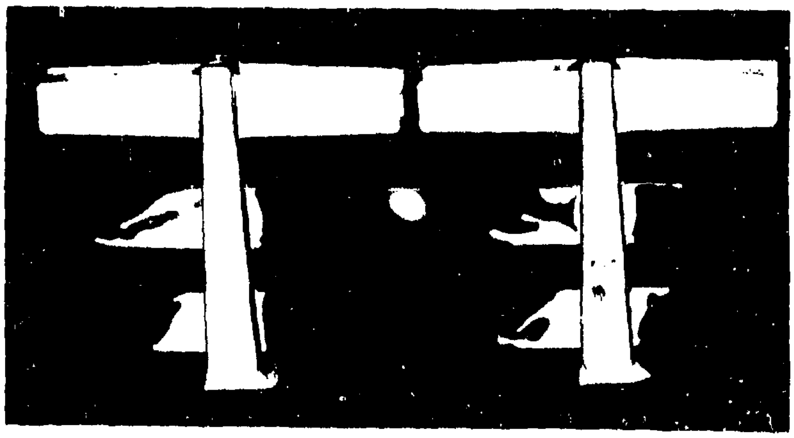
Ti-6Al-4V Alloy
Neg. No. 8-29576

5621S Alloy
Neg. No. 8-29553

IMI700 Alloy
Neg. No. 8-29710

Figure 5. Titanium alloy stylized castings produced by skull melting process at REM (Magn 1/3X).

Ti-6Al-4V alloy with 0.060 in. test sections
Neg. No. 8-29477



5621S alloy with 0.080 in. test sections
Neg. No. 8-29454

Figure 6. Titanium alloy stylized castings produced by induction melting process at TRW (Magn 1/3X).

Table III

Summary of Visual and Radiographic Evaluation of Titanium Stylized Castings

Melting practice	Alloy	Thin section characteristic	Quantity cast	Mold preheat temp.	Visual observation	Radiographic[a] standard conformance
Induction	Ti-6Al-4V	nontapered 0.060 in. thick	2	650F	none filled	No
			1	1000F	none filled	No
			7	1250F	2 filled	No
	5621S	nontapered 0.080 in. thick	4	1250F	3 filled	No
Skull	Ti-6Al-4V	nontapered 0.060 in. thick	9	700F	8 filled	No
	5621S	nontapered 0.060 in. thick	5	700F	5 filled	No
	IMI700	nontapered 0.060 in. thick	4	700F	4 filled	No
	Ti-6Al-4V	tapered 0.060 in. thick	3	700F	3 filled	Yes
	5621S	tapered 0.060 in. thick	3	700F	3 filled	Yes
	Beta III	tapered 0.060 in. thick	4	700F	4 filled	3 Yes 1 No

(a) ASTM E192, Grade 3

3.1.1.2 Radiographic Evaluation

The thin test sections were removed from the heavy section of the stylized specimens prior to radiography to present an optimum situation for X-ray inspection.

In general, radiographs of stylized castings, with nontapered thin sections, showed thin section imperfections corresponding to ASTM E192 Grade 4 or higher regardless of casting process. This was not commensurate with requirements for highly stressed rotating components. Present X-ray standards for impellers (Detroit Diesel Allison specification EIS 675-7) covers precision castings of nickel, iron and cobalt base alloys. This specification, referencing ASTM E192 radiographic standards, requires a grade no worse than 3 on thin sections. The imperfections, as shown in Figures 7 and 8, appeared as dendritic/sponge shrinkage and gas porosity. The spots of porosity in the skull melt castings appeared to be smaller and more evenly distributed than those in the induction melt castings which were more gobular. Large areas of porosity evidenced by the white spots, are plainly visible in Figure 7. These areas were visible by X-ray only. Visually, the sections appeared to be structurally sound. Sectioning of these areas showed a hollow vane effect where the alloy had solidified at the mold walls but failed to fill the center portion.

Subsequently, a 1.5 degree taper was incorporated on each side of the thin sections to aid in feeding during solidification in order to reduce or eliminate the dendritic type shrinkage. The original design, meant to sort out subtle differences in the alloys, had served its purpose. In general, the tapered thin sections of all three alloys, Ti-6Al-4V, 5621S and Beta III, showed radiographic quality that did meet or exceed the grade 3 standard. Representative radiographic prints are shown in Figure 9. No one alloy was significantly better than any other.

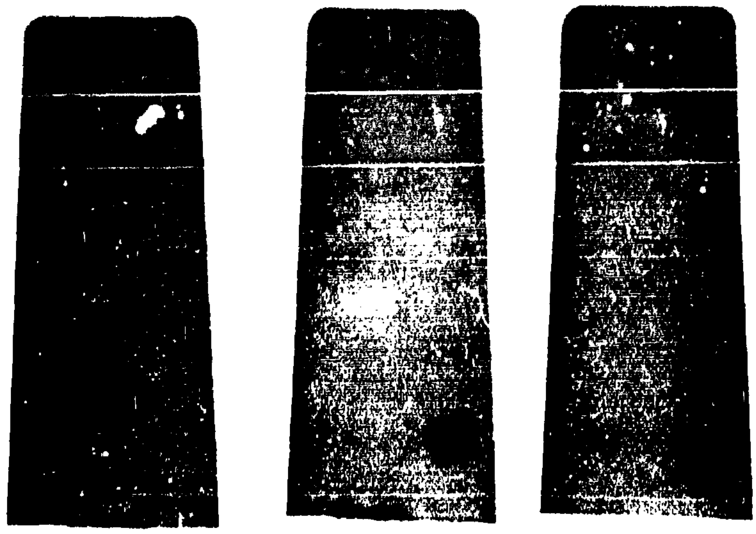
The thick sections of the castings were generally satisfactory. The representative positive prints shown in Figure 10, illustrate the general types of defects noted, i.e. centerline shrinkage and tungsten inclusions. There were a few incidents of isolated gas porosity not associated with the centerline pipe. The gas porosity and inclusions

Ti-6Al-4V Alloy
Neg. No. 8-29579

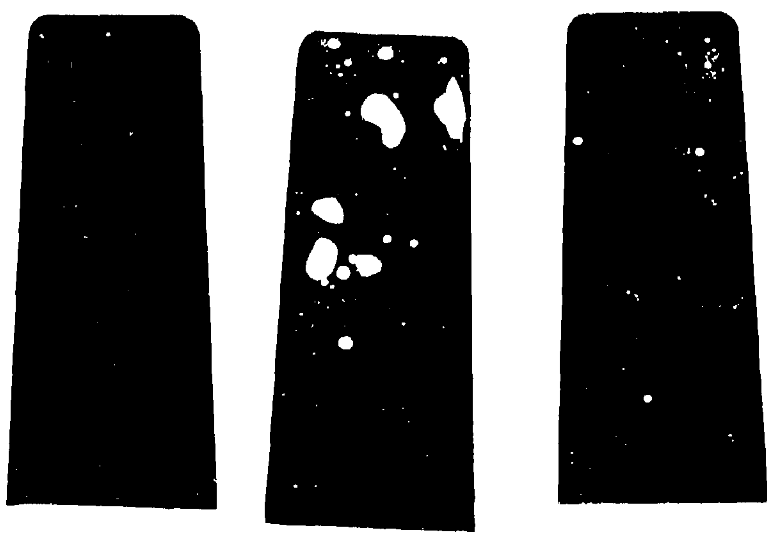
5621S Alloy
Neg. No. 8-29578

IMI700 Alloy
Neg. No. 8-29735

Figure 7. Positive radiographic prints of typical nontapered thin test sections of stylized castings cast by skull melting process by REM. Large white areas are subsurface porosity. (Magn 1/3X)



Ti-6Al-4V Alloy
Neg. No. 8-29472



5621S Alloy
Neg. No. 8-33025

Figure 8. Positive radiographic prints of typical nontapered thin test sections of stylized castings cast by induction melting process by TRW. (Magn 1X)

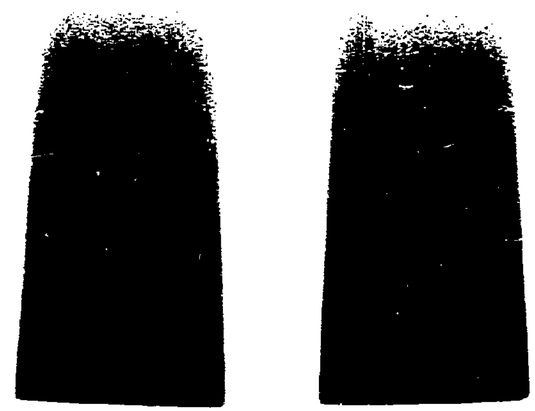


Figure 9. Positive radiographic prints of typical tapered thin test sections of stylized castings cast by skull melting process by REM. (Magn 1X) Neg. No.8-33055

Neg. No. 8-29474

Neg. No. 8-33020

Figure 10. Radiographic prints of typical heavy sections of titanium stylized castings showing centerline shrinkage and tungsten inclusions. The black lines are thermocouple probes. (Magn 1X)

do not reflect on an alloy's inherent castability but are related to routine foundry problems with respect to fabrication of high integrity shell molds.

3.1.2 Heat Treatment

The stylized castings were heat treated prior to mechanical testing. All were solution treated with a protective atmosphere of argon. However, approximately 0.005 in. stock was removed from each side of the thin test sections prior to specimen generation for mechanical testing as a precautionary measure in case some surface contamination had occurred during heat treatment.

The thermal treatments employed were as follows:

Ti-6Al-4V - Solution treatment: 1750F-1 hr.(Argon) + H_2O quench
Age treatment: 1000F-4 hr.(Air) + A/C (STA)

Ti-6Al-4V - Annealing treatment: 1300F-2 hr.(Argon) + A/C

5621S - Solution treatment: 1800F-1 hr.(Argon) + A/C
Age treatment: 1100F-2 hr.(Air) + A/C (STA)

IMI700 - Solution treatment: 1550F-1 hr.(Argon) + A/C
Age treatment: 930F-24 hrs.(Air) + A/C (STA)

Beta III - Solution treatment: 1350F-15 min.(Argon) + H_2O quench
Age treatment: 950F or 900F-4 hrs.(Air) + A/C (STA)

An aging temperature of 950F was utilized for the initial Beta III tensile tests, based on the recommendation of REM. The test results indicated that a lower aging temperature, e.g., 900F, might provide higher strength. Thus, the lower age temperature was used for the remaining Beta III testing.

3.1.3 Physical and Mechanical Properties

3.1.3.1 Chemical Analysis

Chemical analyses were determined for castings of each vendor-alloy combination. Representative analyses are listed in Table IV along with the desired end-item and starting material ingot analyses. Skull melt castings conformed essentially to prescribed aims. Castings produced by the induction melting process were slightly higher in bulk carbon content due, probably, to pick-up from the graphite crucible.

Electron microprobe analyses were conducted on transverse samples from the thin sections of typical stylized shapes in the as cast condition. There was no evidence of tungsten mold material diffusion or other reaction in or on the casting surface. The microprobe analyses did not include evaluation of interstitial elements.

3.1.3.2 Tensile Tests

All tensile specimens were radiographically inspected after machining. The induction melt specimens (TRW) met ASTM E192 Grade 4 or better while the skull melt (REM) specimens met Grade 3 or better. This quality difference is reflected in the lower ductility of the thin induction melt specimen s.

Results of tests on stylized castings of Ti-6Al-4V and 5621S alloys produced by the TRW induction melting process are listed in Table V. Thin section tensile data are given for only annealed material in the Ti-6Al-4V alloy. No solution treated and aged thin section specimens of Ti-6Al-4V alloy were tested due to poor structural integrity. No thin section data were obtained for 5621S alloy due to poor castings fill. Both room temperature and 700F tests were conducted on specimens generated from thick casting sections. Strength of thin and thick sections were comparable although ductility of the thin sections was lower.

Table VI lists room temperature data on thin (flat) and thick (round) section tensile specimens from castings produced by the REM skull melting practice. Elevated temperature data (700F) are given in Table VII. Tensile properties of skull melt castings are summarized graphically in Figures 11, 12, and 13.

Table IV

Chemical Analysis of Titanium Castings Cast by Induction Melting and Skull Melting Processes

	Al	V	C	Fe	Mo	Zr	Sn	O_2	H_2	N_2
Ti-6Al-4V Heat 32142486										
Skull	6.40	4.15	.010	.14	---	---	---	.12	.0040	.008
Induction	6.30	4.08	.080	.22	---	---	---	.15	.0060	.009
Ingot	6.19	4.13	.022	.15	---	---	---	.13	.0060	.011
AMS 4930	5.50-6.50	3.50-4.50	.080 max	.25 max	---	---	---	.13 max	.0125 max	.050 max
Ti-6Al-4V Heat K2322										
Skull	6.40	4.10	.030	.11	---	---	---	.09	.0070	.009
Ingot	6.50	4.20	.026	.09	---	---	---	.14	.0070	.014
AMS 4930	5.50-6.50	3.50-4.50	.080 max	.25 max	---	---	---	.13 max	.0125 max	.050 max
5621S Heat 29420										
Skull	4.80	---	.005	.06	.82	2.16	6.00	.070	.0030	.007
Induction	4.10	---	.060	.05	.78	2.26	5.80	.094	.0037	.002
Ingot	5.00	---	.010	.04	.77	1.90	6.30	.075	.0027	.005
Aim	5.00	---	.015	.07	.80	2.00	6.00	.075	.0075	.005
IMI700 Heat A7454										
Skull	6.28	---	.070	.06	3.92	4.56	---	.180	.0050	.005
Ingot	6.05	---	.060	.04	4.30	4.62	---	.075	.0030	---
EMS 59030	5.00-7.00	---	.150 max	.20 max	3.00-5.00	4.00-6.00	---	.200	.0130 max	---
Beta III Heat K50401										
Skull	---	---	.020	.09	11.90	6.50	4.35	.085	.0044	.019
Ingot	---	---	.010	.01	11.20	6.30	4.70	.130	.0130	.010
Aim	---	---	.030	.04	12.10	6.50	4.35	.130	.0095	.014
5621S Heat S174-01										
Skull	5.10	---	>.010	.09	.81	2.20	6.65	.038	.0022	.009
Ingot	5.08	---	.017	.05	.69	2.07	5.12	.071	.0023	.012
Aim	5.00	---	.015	.07	.80	2.00	6.00	.075	.0075	.005

Table V

Results of Uniaxial Tensile Tests Conducted on Flat and Round Specimens Generated from Castings Produced by the TRW Induction Melting Process

Specimen geometry	Test temp. ^{o}F		Ultimate strength, ksi	0.2% Yield strength, ksi	Proportional limit, ksi	Static modulus, 10^6 psi	Reduction of area, %	Elongation in 1 inch, %
				Ti-6Al-4V Alloy - Annealed				
Flat (Thin)	R.T.		139.2	131.9	107	11.6	(a)	2.5
			142.9	123.0	91	(b)	---	8.6
			139.2	121.5	78	15.3	---	3.1
			131.5	128.7	111	18.3	---	1.9
			143.8	99.0	55	18.6	---	4.1
			133.8	130.2	(b)	13.9	---	1.2
		Avg.	138.4	122.2	88	15.5		3.5
Round (Thick)	R.T.		137.0	125.9	109	17.9	21.0	13.5
			140.0	130.0	92	17.0	16.8	13.4
			141.0	132.0	100	19.5	19.6	12.0
			140.0	128.5	81	18.2	17.6	15.0
		Avg.	139.5	129.1	95	18.1	18.7	13.4
				Ti-6Al-4V Alloy - Solution Treated + Aged				
Flat (Thin)	R.T.		(c)	---	---	---	---	---
Round (Thick)	R.T.		163.0	152.0	132	19.2	16.0	6.9
			158.0	149.5	132	17.6	7.9	5.0
			156.0	151.8	121	19.6	6.3	3.0
			158.2	151.0	128	18.1	3.2	5.0
		Avg.	158.8	151.0	128	18.6	7.6	4.9

Table 7---Continued

Specimen geometry	Test temp. °F		Ultimate strength, ksi	0.2% Yield strength, ksi	Proportional limit, ksi	Static modulus 10^6 psi	Reduction of area, %	Elongation in 1 inch %
			Ti-6Al-4V Alloy - Solution Treated + Aged					
Round (Thick)	700F		105.0	79.2	65	15.0	33.3	13.1
			104.2	78.0	64	14.9	28.1	12.5
			104.8	80.0	63	15.0	31.3	15.0
			115.8	87.5	72	14.0	23.2	15.1
		Avg.	107.4	81.1	66	14.7	28.9	13.9
			5621S Alloy - Solution Treated + Aged					
Flat (Thin)	R.T.		(c)	---	---	---	---	---
Round (Thick)	R.T.		142.4	125.6	101	17.5	7.9	9.5
			139.3	124.6	103	16.8	11.8	6.6
			140.0	124.6	95	17.5	8.7	9.0
			138.3	122.9	100	17.5	8.7	8.9
		Avg.	140.0	124.4	100	17.3	9.2	8.5
Round (Thick)	700F		87.7	70.8	49	15.4	21.1	12.3
			88.7	71.3	49	14.7	21.1	10.5
			87.9	72.5	51	15.7	26.8	12.1
			87.4	70.1	54	(b)	26.0	12.4
		Avg.	87.9	71.1	51	15.2	23.7	11.8

(a) Reduction of area not calculated for flat specimens.

(b) Unsatisfactory stress-strain curve

(c) Tests were not conducted on flat specimens due to the poor quality of the castings (porosity).

Heat treatments:

Ti-6Al-4V - Solution treatment: 1750F-1 hr.(Argon) + H_2O quench
Age treatment: 1000F-4 hrs.(Air) + A/C (STA)

Ti-6Al-4V - Annealing treatment: 1300F-2 hrs.(Argon) + A/C

5621S - Solution treatment: 1800F-1 hr.(Argon) + A/C
Age treatment: 1100F-2 hr.(Air) + A/C (STA)

Table VI

Results of Room Temperature Uniaxial Tensile Tests Conducted on Flat and Round Specimens Generated from Castings Produced by the REM Skull Melting Process

Specimen geometry		Ultimate strength, ksi	0.2% Yield strength, ksi	Proportional limit, ksi	Static modulus, 10^6 psi	Reduction of area, %	Elongation in 1 inch, %
Ti-6Al-4V Alloy - Annealed							
Flat (Thin)		137.4	126.0	111	12.8	(a)	5.9
		135.9	124.5	107	14.8	---	8.3
		136.9	126.2	111	13.1	---	(b)
		134.5	129.2	111	14.1	---	(b)
		135.2	126.1	109	15.3	---	3.8
		137.4	133.0	111	11.8	---	6.0
	Avg.	136.2	127.5	110	13.6		6.0
Round (Thick)		132.5	122.0	100	17.1	10.1	10.3
		131.0	121.0	95	17.4	18.8	11.2
		133.1	123.9	97	17.4	24.0	10.5
		134.0	123.8	94	18.2	15.3	10.0
	Avg.	132.6	122.7	96	17.5	17.5	10.5
Ti-6Al-4V Alloy - Solution Treated + Aged							
Flat (Thin)		164.0	149.2	129	14.9	---	2.5
		155.0	147.1	123	14.8	---	3.5
		147.3	130.8	(c)	---	---	5.0
		143.0	131.2	104	15.7	---	4.5
		177.3	141.8	117	15.2	---	(b)
		162.5	143.7	110	16.8	---	2.5
	Avg.	158.1	140.6	116	15.4		3.6

Table VI---Continued

Specimen geometry		Ultimate strength, ksi	0.2% Yield strength, ksi	Proportional limit, ksi	Static modulus, 10^6 psi	Reduction of area, %	Elongation in 1 inch, %
			Ti-6Al-4V Alloy - Solution Treated + Aged				
Round (Thick)		151.1	137.1	114	17.2	[illegible]	10.[illegible]
		156.0	141.8	120	17.9	[illegible]	[illegible]
		154.5	141.0	109	16.2	[illegible]	8.3
		157.3	145.5	116	15.5	[illegible]	[illegible]
	Avg.	154.7	141.3	115	16.6	[illegible]	8.1
Flat(d) (Thin)		159.0	145.0	116	16.1	---	3.1
		151.5	145.5	118	15.4	---	3.4
		152.0	135.0	103	16.6	---	4.7
		153.5	137.0	99	15.6	---	4.8
		154.0	138.1	101	17.7	---	4.6
		162.2	144.0	95	16.9	---	3.8
	Avg.	155.4	140.8	105	16.4		4.1
			5621S Alloy - Solution Treated + Aged				
Flat (Thin)		123.2	121.3	89	13.8	---	(b)
		135.9	121.8	97	14.1	---	4.0
		143.7	128.6	102	15.4	---	3.5
		137.2	122.2	98	14.7	---	3.6
	Avg.	135.0	123.5	97	14.5		3.7
Round (Thick)		131.9	114.2	85	17.8	19.9	11.2
		139.1	123.0	99	17.2	19.6	12.5
		137.7	122.8	96	17.2	20.4	16.1
		137.2	118.8	87	18.1	19.0	15.0
	Avg.	136.4	119.7	92	17.6	19.7	13.7

Table VI---Continued

Specimen geometry		Ultimate strength, ksi	0.2% Yield strength, ksi	Proportional limit, ksi	Static modulus, 10^6 psi	Reduction of area, %	Elongation in 1 inch, %
			5621S Alloy - Solution Treated + Aged				
Flat(d) (Thin)		125.6	119.4	86	16.3	---	5.6
		132.4	119.1	79	14.9	---	4.3
		127.7	119.3	78	16.6	---	5.8
		132.6	118.9	82	14.5	---	7.7
		136.4	119.9	90	15.0	---	4.6
		134.7	117.5	83	14.8	---	5.1
	Avg.	131.5	119.0	83	15.3		5.5
			IMI700 Alloy - Solution Treated + Aged				
Flat (Thin)		(e)	---	---	---	---	---
Round (Thick)		156.1	153.1	139	17.9	1.6	2.5
		160.0	157.1	139	17.5	2.4	3.0
		172.2	160.0	139	17.5	3.2	3.0
		171.6	156.2	141	17.3	1.6	3.5
	Avg.	164.9	157.7	140	17.5	2.2	3.0
			Beta III Alloy - Solution Treated + Aged				
Flat(d,f) (Thin)		167.5	150.5	130	12.4	---	4.1
		165.5	149.0	124	12.4	---	(b)
		166.8	147.4	127	13.5	---	3.1
		171.0	154.0	130	12.3	---	2.3
		(g)	148.0	120	13.7	---	(b)
		(g)	148.9	126	12.4	---	3.0
	Avg.	167.7	149.6	126	12.8		3.1

Table VI---Continued

Specimen geometry	Ultimate strength, ksi	0.2% Yield strength, ksi	Proportional limit, ksi	Static modulus, 10^6 psi	Reduction of area, %	Elongation in 1 inch %
		Beta III Alloy - Solution Treated + Aged				
Flat(d,n) (Thin)	179.6	177.5	135	14.9	---	2.2
	183.7	181.6	146	15.1	---	1.5
	171.0	160.0	130	13.8	---	(b)
Avg.	178.1	173.0	137	14.6		1.8
Round(f) (Thick)	172.9	160.4	122	15.0	7.2	6.0
	168.4	157.5	126	15.3	12.3	7.5
Avg.	170.6	159.0	124	15.2	9.7	6.7
Round(h) (Thick)	179.4	169.7	136	14.1	3.6	5.7
	179.6	173.5	144	14.3	4.1	3.4
Avg.	179.5	171.6	140	14.2	3.8	4.5

(a) Reduction of area not calculated for flat specimens.

(b) Broke outside gage marks.

(c) Unsatisfactory stress-strain curve.

(d) Specimens generated from tapered thin test sections.

(e) Tests were not conducted on flat specimens due to the poor quality of the castings (porosity)

(f) 950F age temperature.

(g) Failed through a spot of porosity.

(h) 900F age temperature.

Table VI---Concluded

Heat treatments:

Ti-6Al-4V - Solution treatment: 1750F-1 hr (Argon) + H_2O quench
Age treatment: 1000F-4 hrs (Air) + A/C (STA)

Ti-6Al-4V - Annealing treatment: 1300F-2 hrs (Argon) + A/C

5621S - Solution treatment: 1800F-1 hr (Argon) + A/C

IMI700 - Solution treatment: 1550F-1 hr (Argon) + A/C
Age treatment: 930F-24 hrs (Air) + A/C (STA)

Beta III - Solution treatment: 1350F-15 min (Argon) + H_2O quench
Age treatment: 950F or 900F-4 hrs (Air) + A/C

Table VII

Results of 700F Uniaxial Tensile Tests Conducted on Round Specimens Generated from Castings Produced by the REM Skull Melting Process

	Ultimate strength, ksi	0.2% Yield strength, ksi	Proportional limit, ksi	Static modulus, 10^6 psi	Reduction of area, %	Elongation in 1 inch, %
Ti-6Al-4V Alloy - Annealed						
	84.8	67.8	44	14.1	31.3	14.0
	88.5	71.0	52	12.1	31.3	12.9
	88.4	70.0	55	15.7	32.0	15.1
	87.2	69.6	50	14.0	31.0	14.0
Avg.	87.2	69.6	50	14.0	31.4	14.0
Ti-6Al-4V Alloy - Solution Treated + Aged						
	106.8	83.1	57	14.6	39.0	13.0
	109.2	87.7	68	13.7	28.1	13.4
	114.0	84.2	58	14.4	26.6	14.5
	117.5	92.9	73	13.7	28.1	13.4
Avg.	111.8	86.9	64	14.1	30.4	13.5
5621S Alloy - Solution Treated + Aged						
	99.0	75.8	55	15.2	27.2	14.3
	(a)	70.0	44	---	---	---
	92.1	69.0	46	15.0	30.7	13.0
	100.0	76.6	51	14.6	29.3	12.0
Avg.	97.0	72.8	49	14.9	29.0	13.1

Table VII---Continued

	Ultimate strength, ksi	0.2% Yield strength, ksi	Proportional limit, ksi	Static modulus, 10^6 psi	Reduction of area, %	Elongation in 1 inch, %
IMI700 Alloy - Solution Treated + Aged						
	131.9	111.0	91	15.1	11.0	5.5
	128.5	107.1	90	14.6	8.6	5.8
	129.0	103.6	83	14.2	7.9	4.5
	133.4	106.8	86	14.2	10.1	7.9
Avg.	130.7	107.1	87	14.5	9.4	5.9
Beta III Alloy - Solution Treated + Aged						
	(b)126.2	115.2	88	12.2	12.3	6.1
	133.9	117.8	89	12.8	12.4	6.4
Avg.	130.0	116.5	88	12.5	12.4	6.2
	(c)144.2	128.2	77	13.1	13.1	6.6
	143.7	127.5	84	12.5	10.3	4.2
Avg.	143.9	127.8	80	12.7	11.7	5.4

(a) Broke in threads

(b) 950F age temperature

(c) 900F age temperature

Heat treatments:

Ti-6Al-4V - Solution treatment: 1750F-1 hr (Argon) + H_2O quench
Age treatment: 1000F-4 hrs (Air) + A/C (STA)

Ti-6Al-4V - Annealing treatment: 1300F-2 hrs (Argon) + A/C

5621S - Solution treatment: 1800F-1 hr (Argon) + A/C
Age treatment: 1100F-2 hrs (Air) + A/C (STA)

Table VII---Concluded

IMI700 - Solution treatment: 1550F-1 hr (Argon) + A/C
Age treatment: 930F-24 hrs (Air) + A/C (STA)

Beta III - Solution treatment: 1350F-15 min (Argon) + H_2O quench
Age treatment: 950F or 900F-4 hrs (Air) + A/C

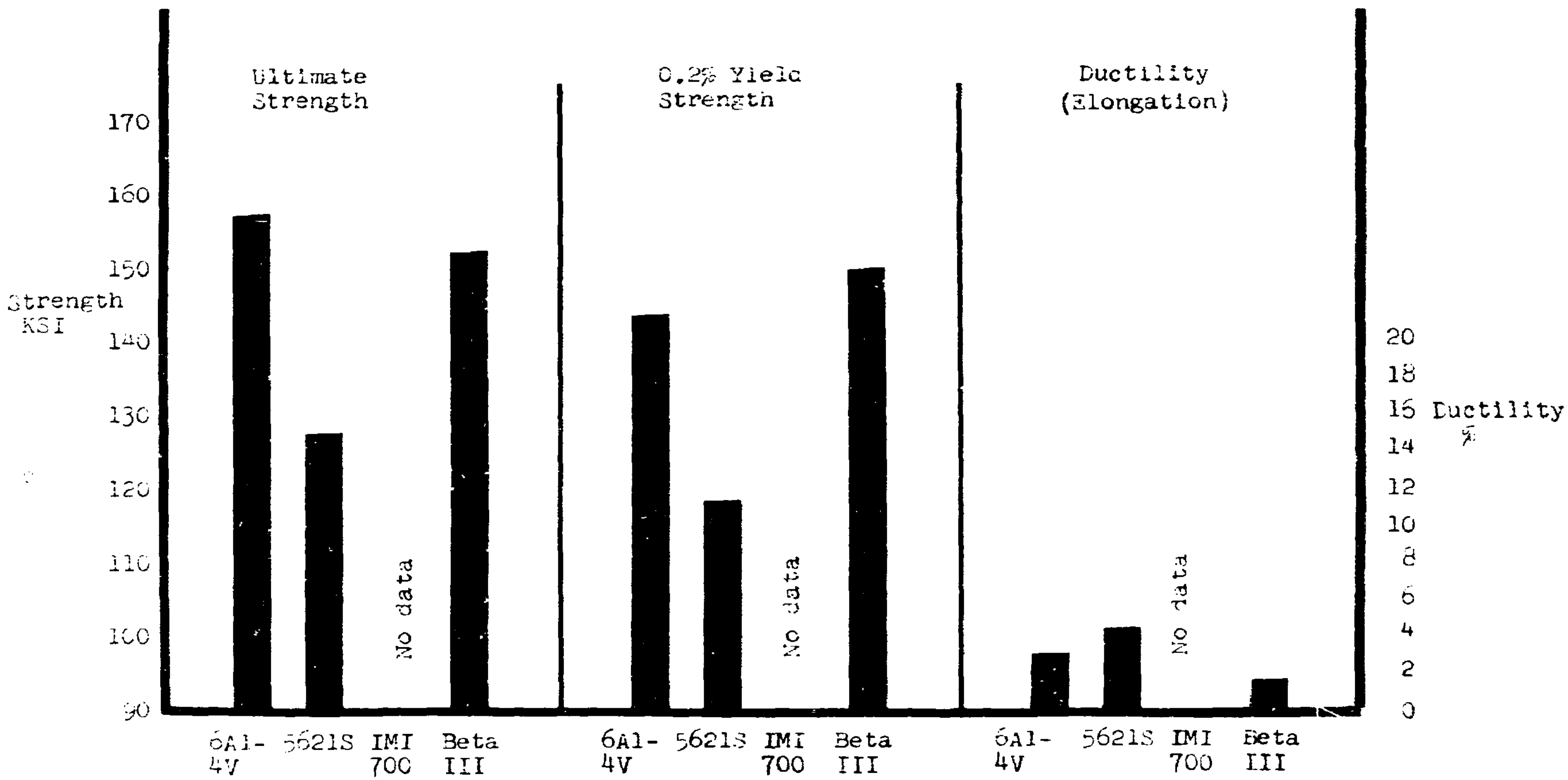


Figure 11. Room temperature uniaxial tensile properties of thin sections in titanium alloy stylized castings produced by the REM skull melting process. All data for solution treated and aged material. Strength values normalized to the density of Ti-6Al-4V alloy.

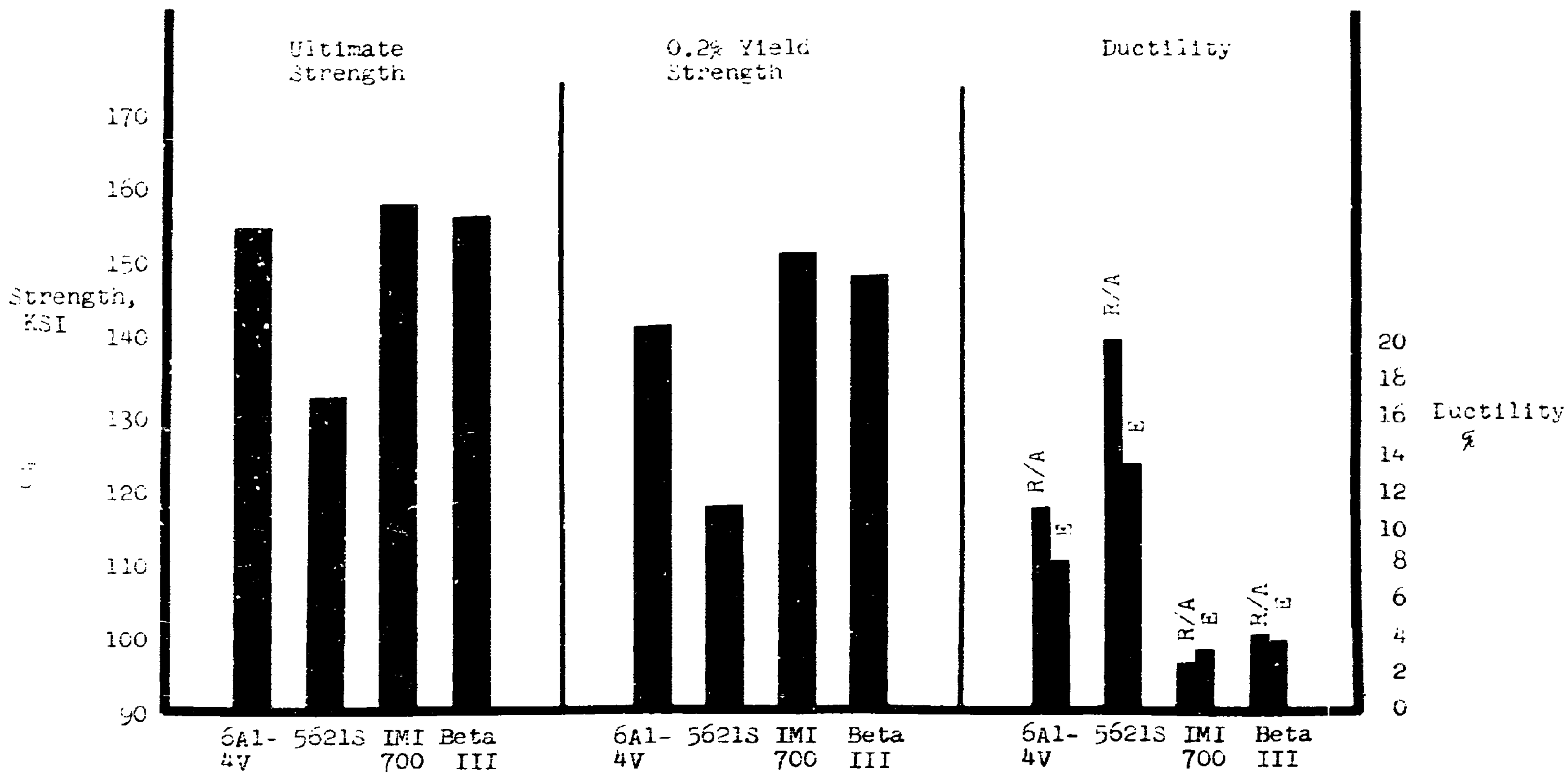


Figure 12. Room temperature uniaxial tensile properties of heavy sectio..s in titanium alloy stylized castings produced by the REM skull melting process. All data for solution treated and aged material. Strength values normalized to the density of Ti-6Al-4V alloy.

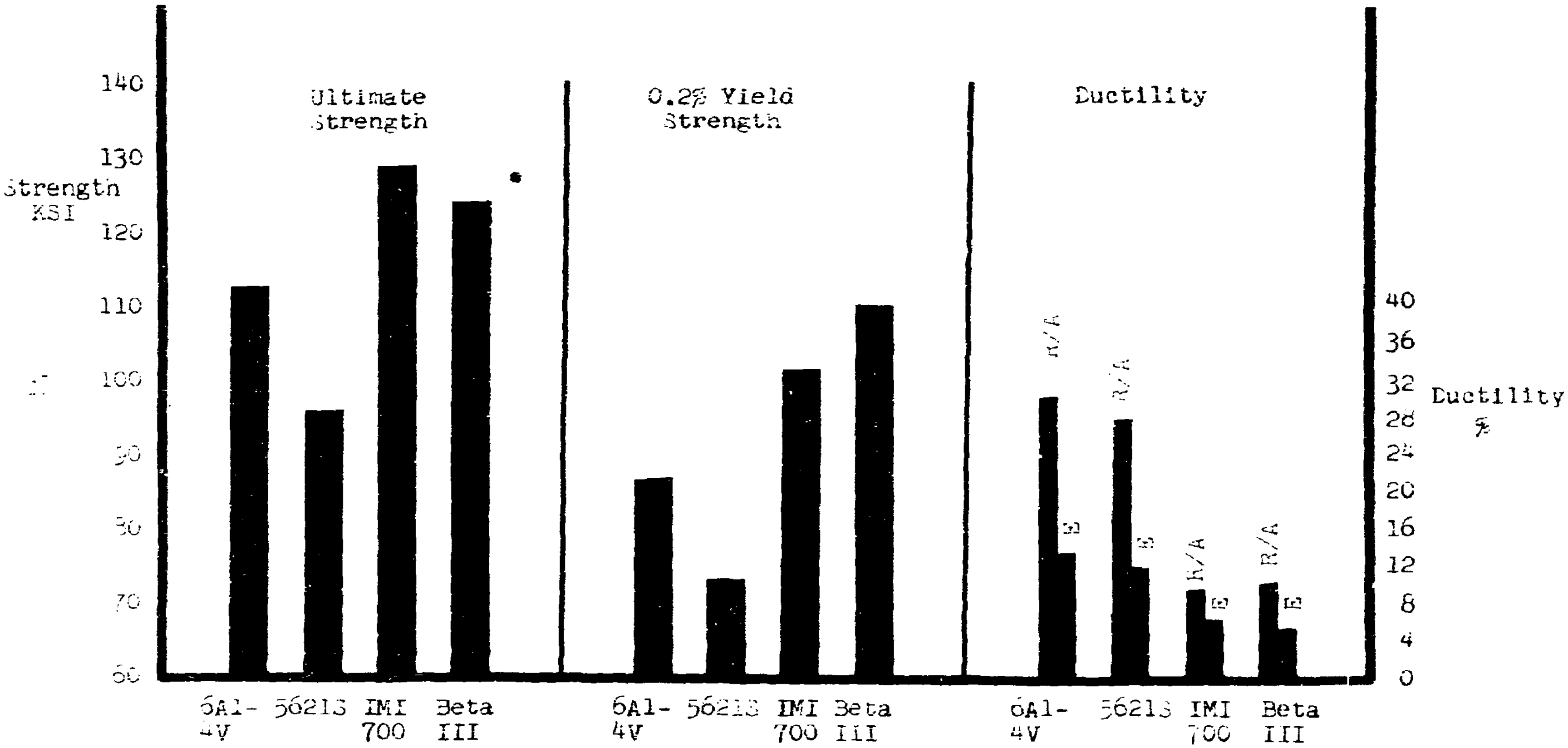


Figure 13. 700F uniaxial tensile properties of heavy sections in titanium alloy stylized castings produced by the REM skull melting process. All data for solution treated and aged material. Strength values normalized to the density of Ti-6Al-4V alloy.

In these figures, ultimate strengths and 0.2% offset yield strengths are normalized with respect to Ti-6Al-4V density. These normalized data present the following rankings based on solution treated and aged strength and ductility when average values are considered. For this comparison no distinction is made between tapered and nontapered thin section shapes of the initial castings. As expected, the lower aging temperature on Beta III provided higher strengths at the expense of a somewhat lower ductility.

Skull Melt Thin Sections, Room Temperature

Ultimate strength	Yield strength	Elongation
Ti-6Al-4V	Beta III (900F age)	5621S
Beta III	Ti-6Al-4V (STA)	Ti-6Al-4V
5621S	Beta III (950F age)	Beta III
	5621S	

Skull Melt Thick Sections, Room Temperature

Ultimate strength	Yield strength	Reduction of area	Elongation
IMI700	IMI700	5621S	5621S
Beta III (900F Age)	Beta III (900F Age)	Ti-6Al-4V	Ti-6Al-4V
Ti-6Al-4V	Ti-6Al-4V	Beta III	Beta III
Beta III (950F Age)	Beta III (950F Age)	IMI700	IMI700
5621S	5621S		

Skull Melt Thick Sections, 700F

Ultimate strength	Yield strength	Reduction of area	Elongation
IMI700	Beta III (900F)	6-Al-4V	6-Al-4V
Beta III (900F Age)	IMI700	5621S	5621S
6-Al-4V and Beta III (950F Age)	Beta III (950F)	Beta III	IMI700
5621S	6Al-4V 5621S	IMI700	Beta III

The trends followed the normal combinations of higher strength, lower ductility.

The tensile data, in general, indicate that the strength level of both thin and thick sections are essentially the same for each material tested. Elongation values were considerably lower in thin section specimens due to specimen geometry effects.

In order to study this geometry effect, flat tensile specimens were machined from the thick center section of a skull melt Ti-6Al-4V casting which had been solution treated and aged. Results of 5 tests (average and range) are listed in Table VIII.

Table VIII

Effect of Specimen Geometry on Room Temperature Uniaxial Tensile Properties of Specimens Generated From Solution Treated and Aged Skull Melt Ti-6Al-4V Castings

Specimen Type	Ultimate strength, ksi	.2% Yield strength, ksi	% Elong. in 1 inch
Flat - Thin section			
Avg.	158.1	140.6	3.6
Range	143.0-177.3	130.8-149.2	2.5-5.0
Flat - thick section			
Avg.	148.8	135.9	4.0
Range	145.2-154.5	126.7-142.6	2.2-5.9
Round - thick section			
Avg.	154.7	141.3	8.0
Range	151.1-157.3	137.1-145.5	6.0-10.0

Results of round bars and thin test sections from similarly heat treated parts are listed for comparison. These limited data suggest slightly lower thin specimen strength for specimens taken from the heavy section. However, it is not possible to reach a statistically valid conclusion to that effect. These data clearly show that the ductility differences between thick and thin section specimens was due to specimen geometry.

A comparison of the average tensile properties for cast titanium alloys, from this program, and wrought forms of the same alloys, from published data, is shown in Table IX. At room temperature, the cast materials showed 87-98% of the wrought yield and ultimate strengths and 81-93% at 700F.

Table IX

Comparison of Average Tensile Properties of Cast and Wrought Titanium Alloys

Alloy		Cast: Ultimate strength, ksi	Cast: 0.2% Yield strength, ksi	Cast: Reduction of area, %	Cast: Elongation, %	Wrought (b): Ultimate strength, ksi	Wrought (b): 0.2% Yield strength, ksi	Wrought (b): Reduction of area, %	Wrought (b): Elongation, %
Room temperature									
Ti-6Al-4V (Annealed)	(a)	136	127	---	6.0	150(1)	140	45.3	15.6
	(b)	132	122	17.5	10.5				
Ti-6Al-4V (STA)	(a)	155	140	---	4.1	165(1)	154	40.4	15.7
	(b)	154	141	10.1	8.1				
5621S (STA)	(a)	131	119	---	5.5	145(2)	125	27.0	14.0
	(b)	136	119	19.7	13.7				
IMI700 (STA)		---	---	---	---	177(1)	170	35.7	15.3
	(b)	164	157	2.2	3.0				
Beta III (STA)	(a)	178	173	---	1.8	190(3)	175	---	7.5
	(b)	179	171	3.8	4.5				
700F									
Ti-6Al-4V (Annealed)	(b)	87	69	31.4	14.0	105(1)	85	45.9	18.6
Ti-6Al-4V (STA)	(b)	111	86	30.4	13.5	121(1)	100	60.5	18.2
5621S (STA)	(b)	97	72	29.0	13.1	105(2)	78	32.0	16.0
IMI700 (STA)	(b)	130	107	9.4	5.9	143(1)	116	49.1	19.5
Beta III (STA)	(b)	143	127	11.7	5.4	155(3)	137	---	7.0

(1) DDAD internal report data.
(2) Preliminary Properties of Titanium Alloy RMI 5621S", DMIC Technical Note, October 16, 1969.
(3) Mechanical Property Data Beta III Titanium", Battelle Memorial Institute, AFML Contract F33615-69-C-1115, December 1969.

(a) Thin section - flat specimens.
(b) Thick section - round specimens.

The tensile ductility of the cast materials was considerably lower than the wrought materials. Based on round bar data, the room temperature elongation of the cast materials ranged from 20 to 98% of the wrought material counterpart with IMI700 showing the lowest percentage and 5621S the highest. At 700F, the cast material elongations ranged from 30 to 82% of the wrought materials - again with the IMI700 showing the lowest and 5621S the highest percentage.

Induction melt specimens of both Ti-6Al-4V and 5621S appear to show somewhat lower ductility as compared to skull melt specimens. Chemical analysis shows a higher carbon content in the induction melt specimens which might attribute to lower elongation and reduction of areas.

3.1.3.3 Dynamic Modulus Tests

Resonant (fundamental bending) frequencies were recorded for several vane segments prior to machining into tensile specimens. Results of dynamic modulus in bending tests are given in Table X. These data are comparable to values for wrought material.

3.1.3.4 High Cycle Fatigue Tests

Cantilever beam specimens of solution treated and aged titanium alloys (6Al-4V, 5621S and Beta III) were tested at room temperature in the fundamental bending mode. Specimen geometry and calibration strain gage locations are shown in Figure 14.

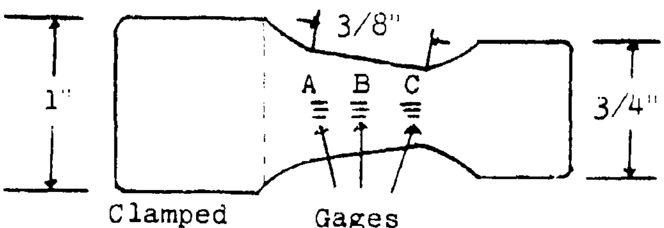


Figure 14. Sketch of high cycle fatigue specimen and strain gage locations

Table X

Room Temperature Dynamic Modulus of Elasticity For Skull Melt Stylized Castings

Specimen Identification	Modulus of Elasticity 10^6 psi
Ti-6Al-4V (Annealed)	
AA 2-2-1	16.0
AA 2-2-2	16.2
AA 1-3-1	17.0
AA 1-3-2	16.4
AA 4-2-1	15.5
AA 4-2-2	16.3
Ti-6Al-4V (STA)	
AA 3-1-1	17.2
AA 3-1-2	16.6
AA 2-1-1	16.8
AA 2-1-2	17.2
AA 1-2-1	17.5
AA 1-2-2	17.5
5621S (STA)	
BB 1-3-1	16.5
BB 1-3-2	16.9
BB 4-3-1	16.9
BB 4-3-2	16.6
BB 5-3-1	14.7
BB 5-3-2	16.7

Modulus derived from: $$\frac{5.43\ F^2\ L^3 W \times 10^{-6}}{wt^3}$$

Where F = resonant frequency, cps
L = length of rectangular specimen, in.
W = weight, grams
w = width of rectangular specimen, in.
t = thickness of rectangular specimen, in.

Strain gages (ED-OY-062AK-350) were applied at location A on all specimens while Band C location gages verified that the tapered section of the specimen was constant stress.

Adjusted 5 x 10^6 cycle endurance limits are presented in Table XI.

Table XI

Cantilever Beam Fatigue Test Results (Fundamental Mode) for Skull Melt Stylized Castings

Alloy	Adjusted 5 x 10^6 Cycles Endurance Limit, psi
Ti-6Al-4V (STA)	54,000
	70,000
	55,300
Ti 5621S (STA)	26,300
	29,500 (a)
	25,000 (b)
Ti Beta III (STA)	33,500
	47,500
	42,000 (c)

(a) 0.44 x 10^6 cycles actual

(b) 3.0 x 10^6 cycles actual

(c) 0.06 x 10^6 cycles actual

The data for the 6Al-4V alloys are comparable to wrought values, which are in the 50,000 - 70,000 psi range. The highest value, 70,000 psi, occurred on a thin 0.039 in. specimen. The thicker specimens failed at an adjusted stress level equal to approximately 35% of the ultimate tensile strength. The thin specimen represented 45% of the tensile strength. The data on the 5621S and Beta III alloys are much lower than the expected values of 40-60% of the ultimate tensile strength. These specimens failed at adjusted endurance stress levels of approximately 20 and 24 per cent of thin tensile strength respectively which is what one would expect with notched specimens. Data are not available at this point to adequately explain the lower than expected results. No abnormalities in internal soundness, microstructure, specimen preparation or tests were observed.

3.1.3.5 Ballistic Impact Tests

Results of ballistic impact tests conducted at room temperature with impact energies to 7 foot pounds (755 fps velocity) are given in Table XII . The data show that all of the heat treated Ti alloy castings, except IMI700, were relatively insensitive to crack formation. The nontapered specimens with heat treated surfaces were more resistant to impact deformation than tapered specimens which were machined after heat treatment to provide specimens of uniform thickness. The high resilience of the heat treated surface is attributed to the presence of a 0.0002 in. thick alpha stabilized case which is known to be of substantially higher hardness than the normal alpha-beta structure and thus is more resistant to deformation. Similar behavior was noted in the baseline specimens of heat treated wrought Ti-6Al-4V.

3.1.4 Metallographic Evaluation - Stylized Castings

Metallographic examination was conducted to investigate 3 predominant items:

- Identification of radiographic defect indications
- Possible surface effects due to the casting process and the subsequent heat treating.
- General structure and grain size

Three basic types of casting process defects were noted. Two of these defects are illustrated in Figure 14. These examples of gas porosity and dendritic/sponge shrinkage were discernible to varying degrees in castings of each alloy. However, as noted under Radiographic Evaluation, Item 3.1.1.2, ASTM E192, Plate 3 quality was met in tapered thin sections. Since mechanical test specimens were selected from the prime areas (minimal radiographic indications), the casting process defects did not affect results. Occasional examples of inclusions were noted but these were generally so small that no attempts were made to analyze them.

Metallographic, microhardness and electron microprobe analyses were conducted on as cast specimens to determine whether any contamination of the casting

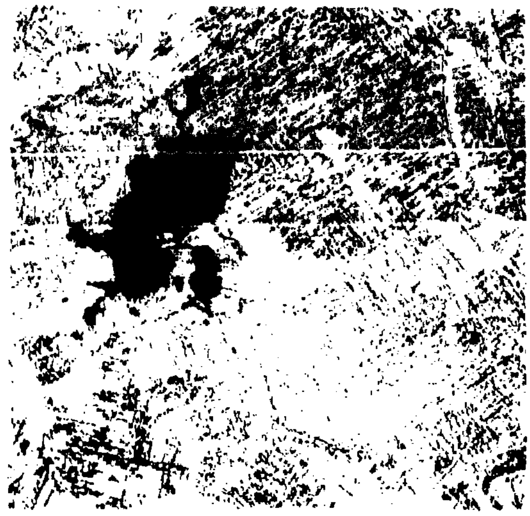
Table XII

Record of Ballistic Impact Tests on Thin, 0.055-0.060 in., Titanium Alloy Specimens--Skull Melt Unless Otherwise Indicated

Alloy	2 (404 fps)	4 (570 fps)	6 (700 fps)	7 (755 fps)
	Impact Level - ft. lbs			
Wrought (Heat Treated Surface)				
Ti-6Al-4V	N	N	N	---
(STA as heat	N	N	N	---
treated surface)	---	---	---	N
Cast (Nontapered Thin Section - Heat Treated Surface)				
Ti-6Al-4V (STA)[(a)]	N	N	N	---
	---	---	N	N
Ti-6Al-4V (STA)	N	N	N	---
	---	---	N	N
	---	---	N	N
IMI700 (STA)	S	S	S	---
	S	S	S	---
	---	---	---	S
	---	---	---	S
Cast (Tapered Thin Section - Machined Surface)				
Ti-6Al-4V (STA)	N	O	O	C
	N	N	O	O
	N	O	O	---
5621S (STA)	N	N	N	---
	---	N	O	O
Beta III (STA)	N	N	N	---
	---	N	O	N
	---	---	N	N

(a) Induction melt abbreviations.
STA - Solution treated and aged
N - No crack
O - Orange peel effect in pushed out metal
C - Cracked circumferentially around bulge
S - 0.5-1.0 in. cracks radiating from impact point

Gas Porosity



Neg. No. 8-29910

Dendritic/ Sponge Shrinkage

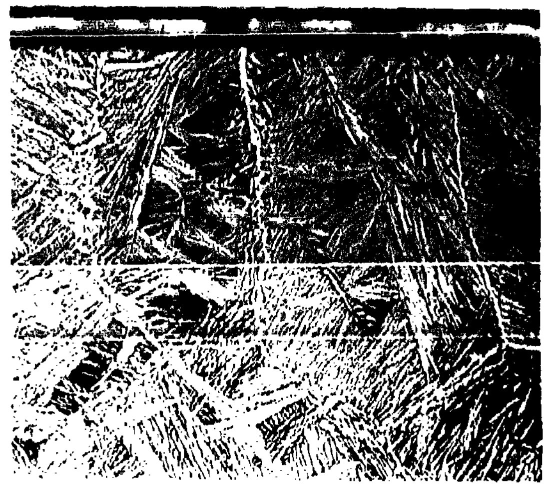
Neg. No. 8-29908

Figure 14. Typical examples of defects in cast titanium alloys detected by radiographic examination. (Keller's Etchant) (Magn: 100X)

surfaces had occurred due to mold reaction. The photomicrographs in Figure 15 show no evidence of contamination. This indication was substantiated by the negative results of microhardness and electron microprobe surveys.

Since it was desired to fully heat treat materials to maximize available mechanical strength, post heat treatment (STA) metallographic examinations were made of the surface of thin test sections. Figure 16 shows the presence of a thin ($\sim$ 0.0002 in.) layer of alpha stabilized material in a specimen of Ti-6Al-4V. Since this surface layer is known to be brittle, it was decided to remove a 0.002 in. layer from the surface of all test specimens to eliminate the possible contaminating influence of this layer on mechanical property data. Later use of a tapered configuration for thin test sections required surface removal for specimen generation. The thick test sectioned surfaces were completely removed during specimen generation.

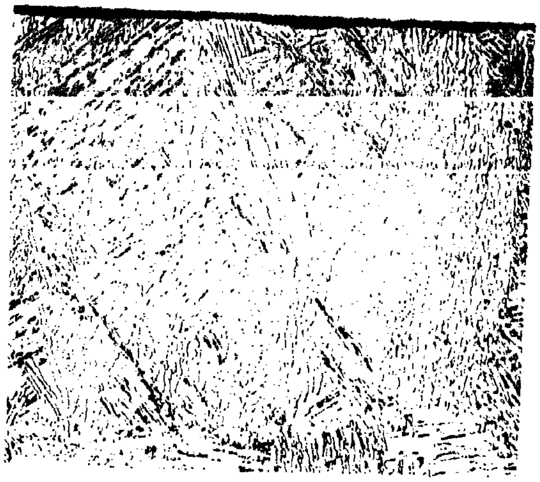
The remainder of metallographic studies on the various alloys and castings showed a wide range of structures and grain sizes. Typical annealed structures of Ti-6Al-4V alloy representing each casting process are shown in Figure 17. The remaining photomicrographs are included to show the wide structural differences of solution treated and aged Ti-6Al-4V (Figure 18), 5621S (Figure 19), IMI700 (Figure 20) and Beta III (Figure 21). There were essentially no differences in structure noted, except for grain size, between heavy and thin sections cast by a given process, or between castings produced by induction and skull melting. Thin test sections were normally fine grained and thick test sections were generally coarser. The grain size determination was conducted by comparing a specimen at 10 diameters with plate 1 of ASTM E1/2 which relates to examination at 100 diameters. Table XIII lists the observed ranges.



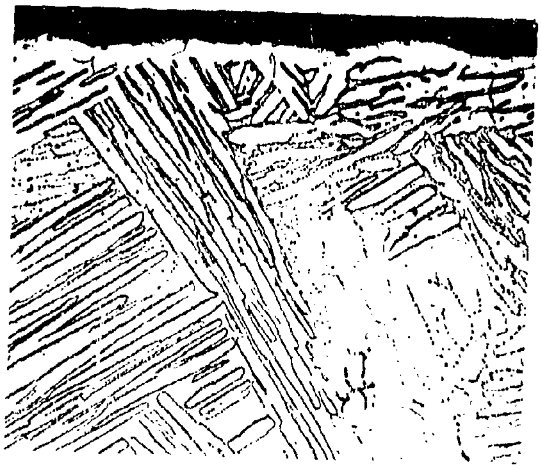
Magn 100X Neg. No. 8-29564

Magn 500X Neg. No. 8-29561

Figure 15. Typical as cast surface of Ti-6Al-4V alloy thin test section cast by the induction melting process. (Ni Plated - Keller's Etchant)



Magn 100X Neg. No. 8-29563



Magn 500X Neg. No. 8-29562

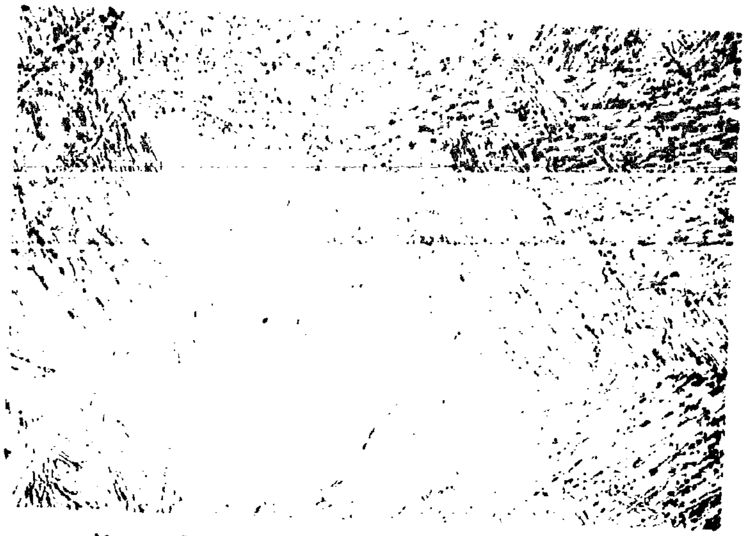
Alpha Stabilized Surface

Figure 16. Illustration of surface effect related to heat treatment in Ti-6Al-4V alloy casting, STA condition. (Keller's Etchant)

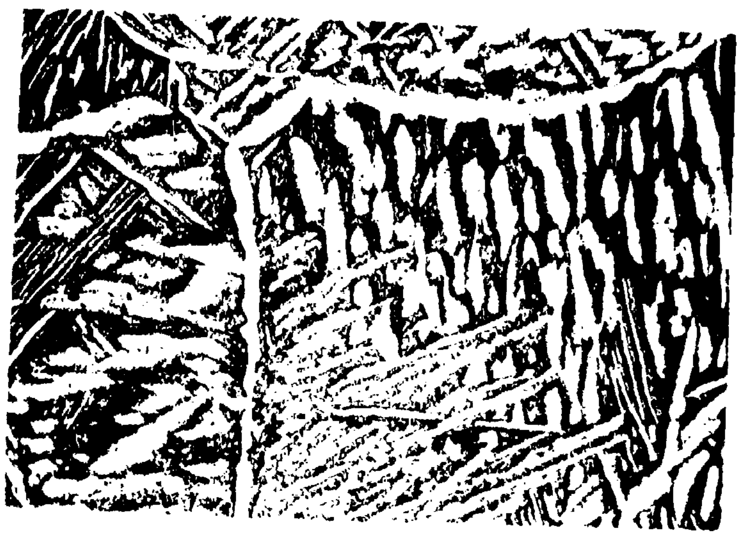
Skull Melt Neg. No. 8-30598

Induction Melt Neg. No. 8-30631

Figure 17. Typical structures of annealed (1325F-2 hrs) Ti-6Al-4V castings. (Keller's Etchant) (Magn 100X)

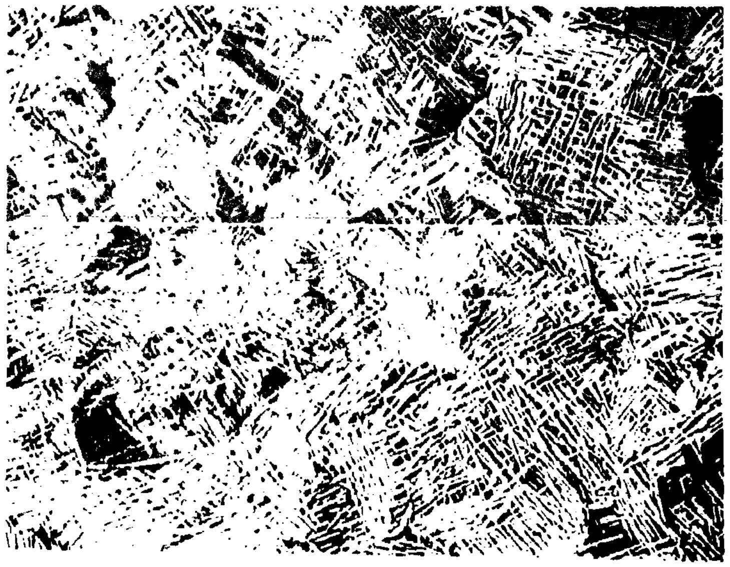


Magn 100X Neg. No. 8-33070

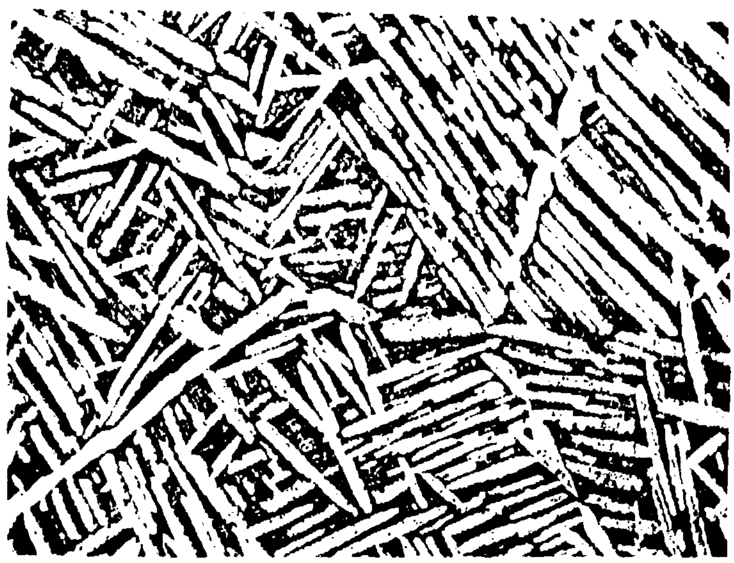


Magn 500X Neg. No. 8-33072

Figure 18. Typical microstructure of Ti-6Al-4V alloy castings in the STA condition. (Keller's Etchant)



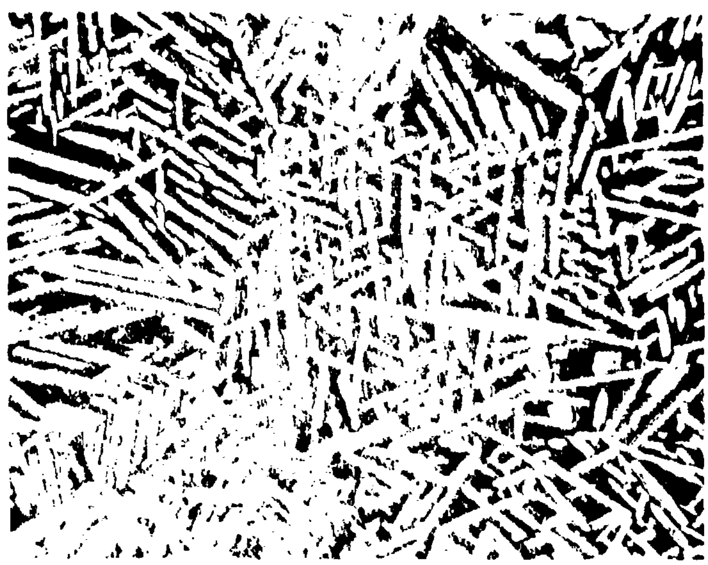
Magn 100X Neg. No. 8-33091



Magn 500X Neg. No. 8-33088

Figure 19. Typical microstructure of 5621S alloy castings in the STA condition. (Keller's Etchant)

Magn 100X Neg. No. 8-33090



Magn 500X Neg. No. 8-33089

Figure 20. Typical microstructure of IMI700 alloy castings in the STA condition. (Keller's Etchant)

Magn 100X Neg. No. 8-33082

Magn 500X Neg. No. 8-33079

Figure 21. Typical microstructure of Beta III alloy castings in the STA condition. (Krolls Etchant)

Table XIII

Grain Size Determinations for
Titanium Alloy Stylized Castings

Alloy	Casting Process	
	Induction	Skull
Ti-6Al-4V Thin	6-8	8-9
5621S Thin	9.5	8
IMI700 Thin	---	9.5-10
Beta III Thin	---	8
Ti-6Al-4V Thick	1-3 pred.1.5	50% 1-1.5 50% 3-3.5
5621S Thick	1-4 pred.3	1.5-3
IMI700 Thick	---	2-4 pred.3
Beta III Thick	---	3

3.1.5 Instrumentation

Molds were instrumented to provide cooling curves which could be reliably related to microstructure and mechanical properties in thick and thin cast sections. The ultimate goal was, of course, to use instrumentation on a production basis to optimize and monitor the casting practice and predictably create desired structure-property relationships in selected areas of complex castings.

A summary of the reliable curves obtained in the program is given in Table XIV. Considerable difficulty was encountered in generating the curves. Problems included shorted and/or open thermocouple leads due to splatter of the melt during pour, and electrical noise pickup in the recording instruments. The cooling curves obtained are shown in Figure 22.

There was considerable spread in the cooling curves obtained from thermocouples located in the ceramic shell mold for castings poured using essentially identical foundry parameters. Some of the more obvious factors that could cause this variability are:

- o Variation in mold temperature -- the mold temperature varied as much as ± 50F, depending on the melting practice.
- o Variation in melt temperature -- the metal temperature for the skull process is unknown and can vary considerably.

Table XIV

Summary of Cooling Curves Obtained From Instrumentation of Titanium Stylized Castings

Casting process	Alloy	Pour No.	Cooling Curves: Thin Section Cavity	Thin Section Shell	Thick Section Cavity	Thick Section Shell
Induction (nontapered)	Ti-6Al-4V	1	a	c	a	a
		2	a	yes	a	c
		3	a	a	a	c
		4	yes	yes	c	c
		5	c	yes	c	c
		6	yes	a	a	a
		7	yes	yes	a	c
		8	yes	a	a	c
		9	a	yes	b	a
		10	yes	b	b	c
	5621S	1	a	yes	a	yes
		2	a	c	yes	yes
		3	c	c	a	c
		4	a	yes	yes	c
Skull (nontapered)	Ti-6Al-4V	1	b	c	b	yes
		2	b	yes	b	yes
		3	b	yes	b	c
		4	b	yes	b	yes
		5	b	c	b	c
		6	b	c	b	yes
		7	b	yes	b	yes
		8	b	c	b	c
		9	b	yes	b	c
	5621S	1	b	yes	b	yes
		2	b	yes	b	yes
		3	b	c	b	yes
		4	b	yes	b	c
		5	b	yes	b	yes
	IMI700	1	b	c	b	yes
		2	b	yes	b	yes
		3	b	yes	b	c
		4	b	yes	b	yes

Table XIV Continued

Casting process	Alloy	Pour No.	Cooling Curves: Thin Section Cavity	Thin Section Shell	Thick Section Cavity	Thick Section Shell
Skull (tapered)	Ti-6Al-4V	1	a	c	a	c
		2	a	yes	yes	c
		3	a	c	a	c
		4	c	yes	yes	yes
		5	c	yes	a	c
		6	c	yes	a	c
		7	c	yes	c	yes
		8	c	yes	c	yes
		9	c	c	a	yes
		10	c	yes	c	c
		11	b	c	b	yes
		12	b	yes	b	yes
		13	b	c	b	a
	5621S	1	b	c	b	c
		2	b	c	b	c
		3	b	c	b	c
	Beta III	1	yes	c	yes	c
		2	yes	a	yes	a
		3	b	a	b	c
		4	b	c	b	c

a - Electrical noise pickup made curve unreadable

b - No thermocouple

c - Malfunction - short, open, too erratic, etc. after pour.

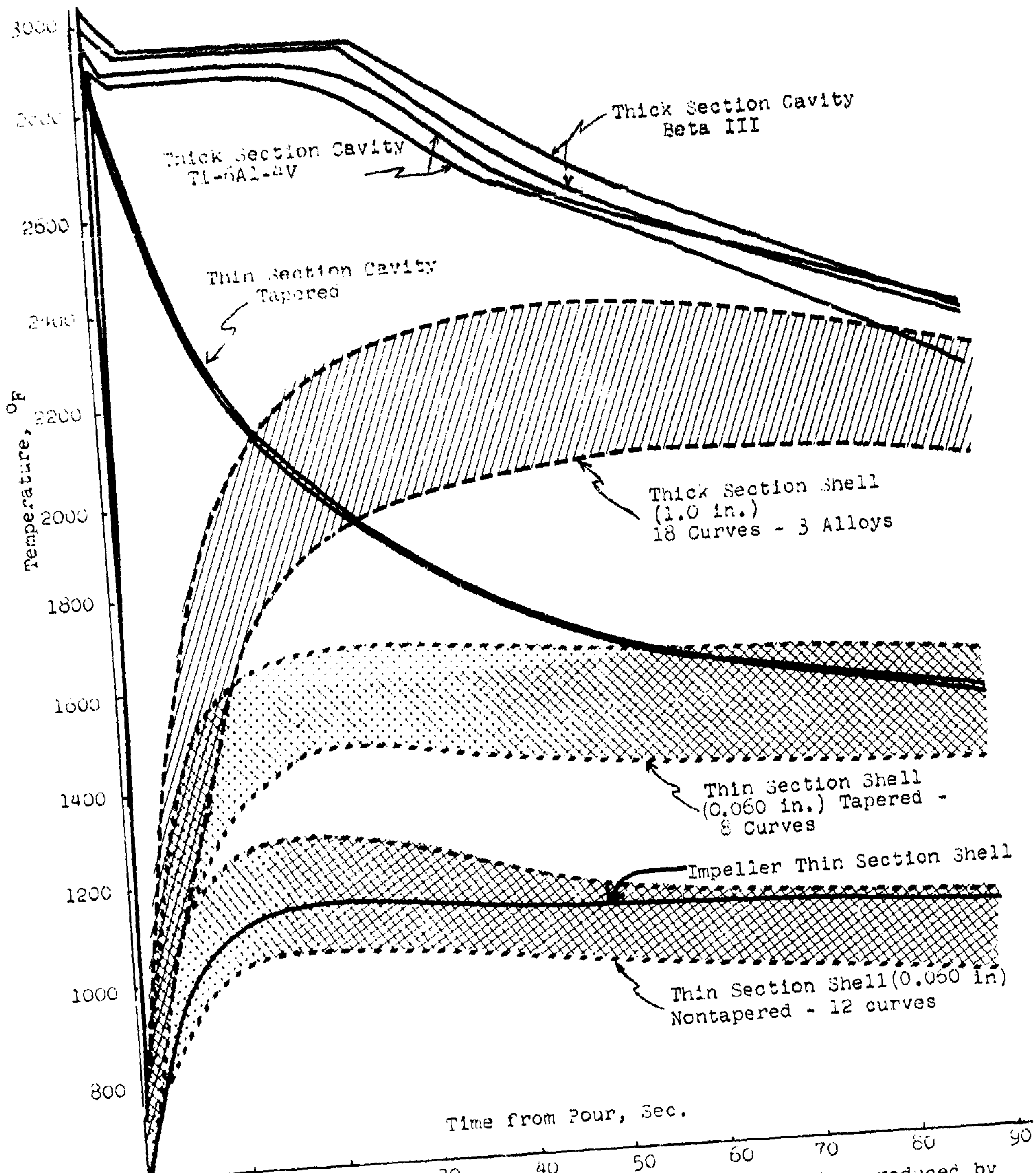


Figure 22. Cooling curves from titanium stylized casting produced by the REM skull melting process. Mold preheat temperature: 700F

- Accuracy in positioning thermocouple -- any variation in the thickness of the first two shell dips would result in a variation of the couple position.

- Total shell thickness -- inherent variations in mold thickness that occur in non-automated mold fabrication influence the cooling characteristics of the mold.

In addition, there was no correlation between the mold cooling curves for the thick and thin sections, i.e., a curve falling in the upper portion of the thick section range did not necessarily correspond to a curve falling in the upper portion of the thin section range. This was also true for corresponding cavity and mold curves. In fact, there appeared to be as much variation between the curves for a casting as there was between shell mold curves for different castings.

The cavity curves were more consistent than the mold curves, i.e., less spread. This is understandable since some of the factors accounting for the variability in the shell mold curves are less influencial on cavity curves. The initial transient temperature of the cavity, during the first few seconds after pour, were not reflected in the mold curves due to the inherently lower location related sensitivity of the shell mold thermocouples. However, it is questionable whether the shape of the cavity curve in these first few seconds bears any practically useful relationship to the structure or properties of the casting.

There appeared to be no correlation between the mold temperature curves (thick section vs thin section) and the basic microstructure or tensile properties. The only obvious correlation was with the macro grain size. As expected, the higher temperature curves for the thick sections correlate with the larger grain sizes in those sections.

Because of the aforementioned variations and lack of positive correlations the cooling curve data were not submitted for mathematical analysis.

In summary, it does not appear that mold instrumentation is a useful tool for monitoring the casting practice or predictably creating specific structure-property relationships in titanium alloy castings.

3.2 PHASE II - OPTIMUM ALLOY EVALUATION

3.2.1 Alloy Selection

A review of Phase I tensile data indicated that cast Ti-6Al-4V alloy (STA) offered the best combination of properties consistent with needs of high speed rotating components, e.g., an impeller, over the anticipated operating temperature range for such components. IMI700 and Beta III castings exhibited insufficient ductility, while 5621S alloy was deficient in strength. In addition, Ti-6Al-4V alloy castings exhibited distinctly superior high cycle fatigue characteristics. Thus, Ti-6Al-4V alloy was chosen for Phase II evaluation.

3.2.2 Low Cycle Fatigue Tests - Stylized Castings

Isothermal fully reversed strain controlled low cycle fatigue (LCF) tests were performed at room temperature and 700F on specimens taken from the thick sections of ten (10) stylized castings. The data are reported as strain range versus cycles to failure for axially loaded specimens. Crack initiation lives are also included. Both elastic and plastic strain values followed curvilinear paths. A comparison of total strain range vs cycles to failure for cast Ti-6Al-4V (STA) at room temperature, 700F and wrought Ti-6Al-4V (STA) at 700F is shown in Figure 23 and cyclic life values are given in Table XV. The cast and wrought LCF lives at 700F are essentially the same for strain ranges less than 1.0%. Cast titanium room temperature LCF lives are $<$ cast titanium LCF 700F lives below 3000 cycles ($\Delta\epsilon_t$ = 1.3%) and $>$ cast Ti 700F lives above 3000 cycles. This behavioral change can be attributed to lower plastic strain resistance of cast Ti at room temperature for short lives ($<$ 3000 cycles) and its higher elastic strain resistance at longer lives ($>$ 3000 cycles).

The summary of low cycle fatigue results, Table XVI lists cycles to failure and crack initiation, stress ranges and elastic, plastic and total strain values for all tests conducted. The strain-life plots are shown in Figures 24 and 25.

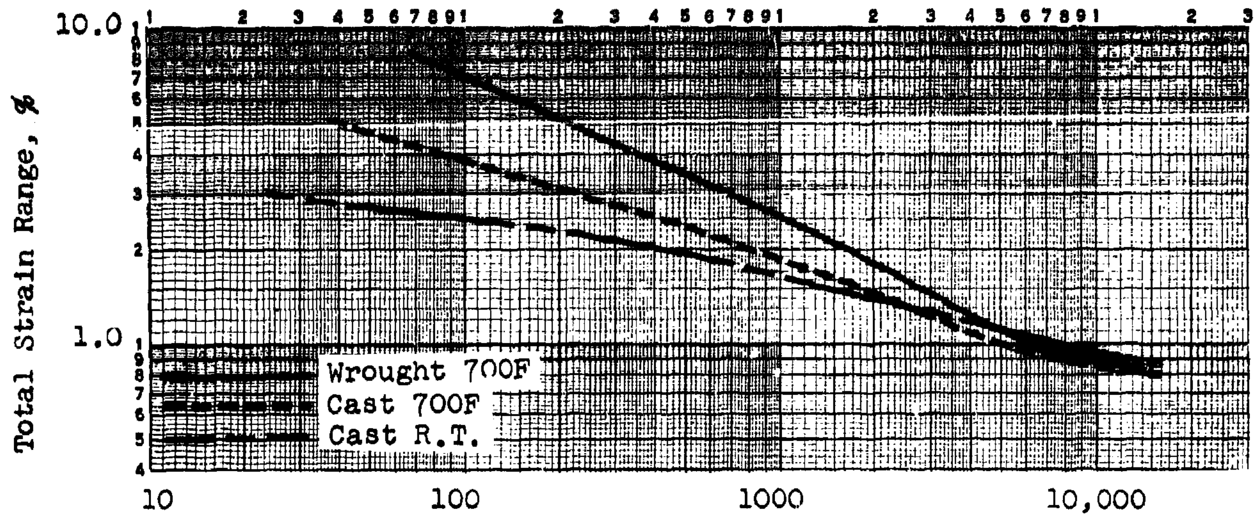


Figure 23. Comparison of low cycle fatigue properties of cast and wrought Ti-6Al-4V (STA)

Table XV

Comparison of Strain Range to Cycles for Cast and Wrought Ti-6Al-4V (STA)

	Cycles to Failure		
Strain Range, %	Cast R.T.	Cast 700F	Wrought 700F
3.0	26	225	690
2.0	400	845	1650
1.5	1600	1820	2850
1.0	8400	5300	5500
0.9	13500	8000	8300

Table XVI

Summary of Low Cycle Fatigue Results
For Cast Ti-6Al-4V (STA)

Spec. No.	Cycles to Crack Initiation(1)	Cycles to Failure N_f	Elastic Stress Range $2\sigma_a$, ksi	Cyclic Values* Strain Range, % Elastic $\Delta\epsilon_e$	Plastic $\Delta\epsilon_p$	Total $\Delta\epsilon_T$
		Room Temperature 20 cpm				
5-2	8	24	326.3	1.954	1.219	3.173
9-1	70	103	295.0	1.770	0.750	2.520
2-2	316	561	274.3	1.643	0.362	2.005
8-1	1413	1531	231.0	1.380	0.144	1.524
3-2	2722	4394	184.4	1.104	0.089	1.193
6-1	6354	6657	173.5	1.040	0.030	1.070
10-1	14889	16149	149.0	0.890	0.007	0.897
		700F 5 cpm				
2-1	14	40	220.8	1.566	3.493	5.059
7-1	75	112	219.0	1.553	2.335	3.888
3-1	162	226	191.2	1.356	1.723	3.079
10-2	509	627	180.2	1.278	0.857	2.135
5-1	1085	1339	158.7	1.126	0.507	1.633
8-2	2705	3227	148.0	1.050	0.173	1.223
6-2	5609	6002	126.3	0.896	0.071	0.967
1-1	11893	12873	118.0	0.836	0.006	0.842

* Approximate half-life values

(1) Values taken for a 100 pound load drop

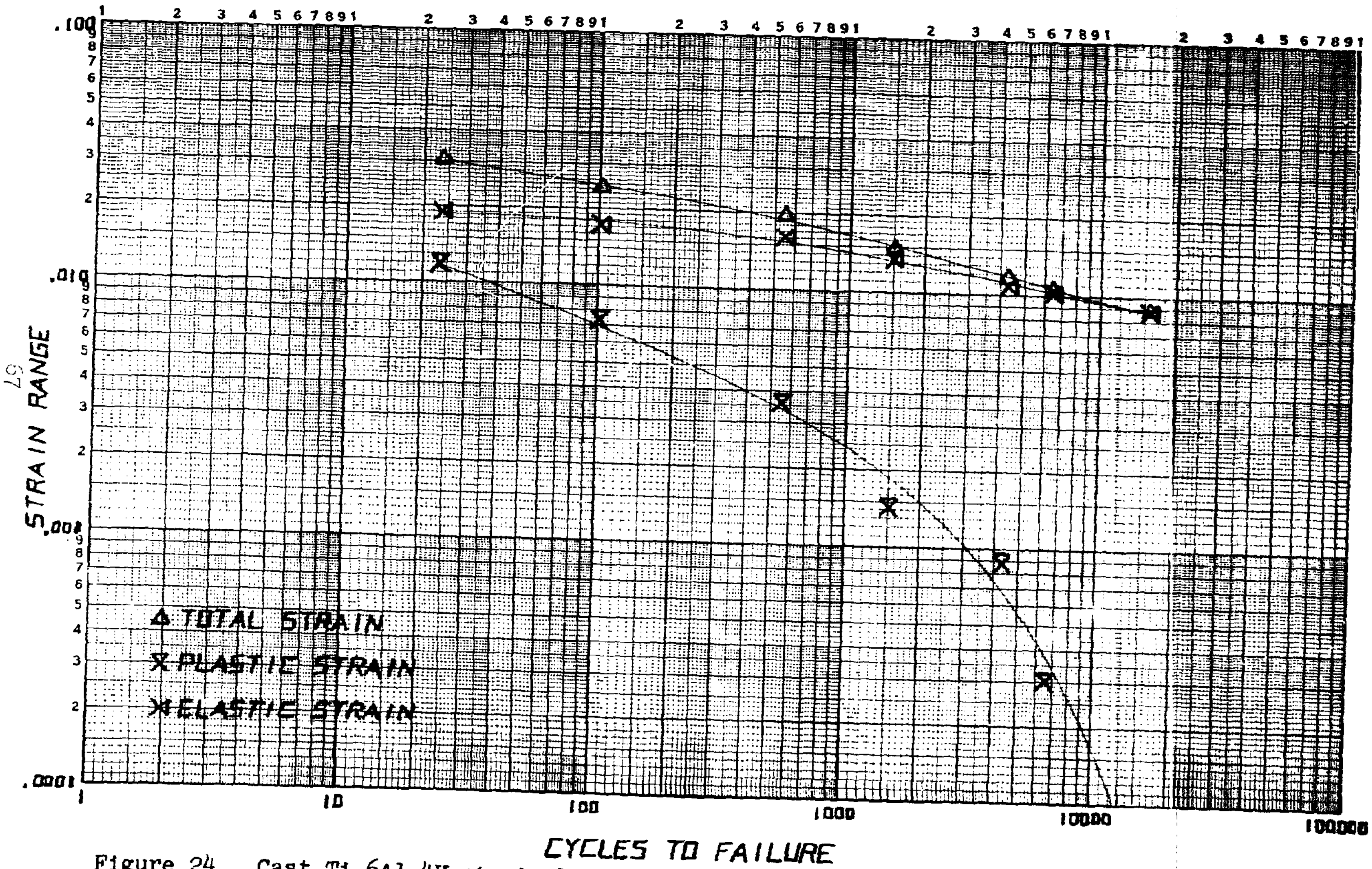


Figure 24. Cast Ti-6Al-4V strain-life plots - room temperature, 20 cpm

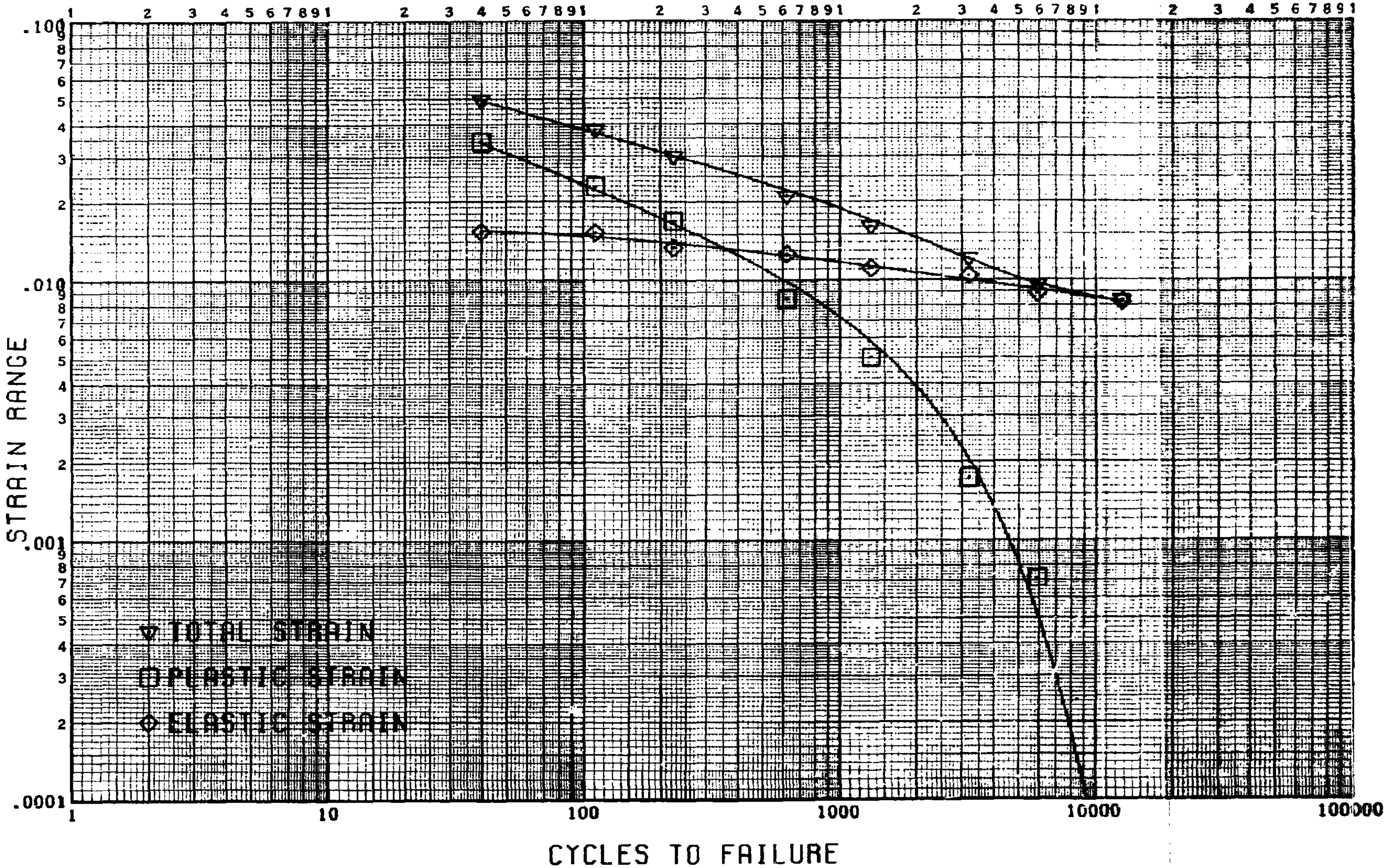


Figure 25. Cast Ti-6Al-4V (STA) strain-life plots - 700F, 5 cpm

3.2.3 Tensile Tests - Impeller Casting

The cast impeller used for tensile property evaluation is shown in Figure 26. The gating was removed prior to heat treatment. After solution treating and aging, the casting was further sectioned to provide specimens for tensile tests. The only area suitable for specimens was the base plate. To provide a more accurate determination of strength, five flat chordal specimens (subsize) and 5 flat radial specimens were made, alternating the location to thus provide 1 radial, 1 chordal, etc., as shown in Figure 27. Results of testing are given in Table XVII. The data indicate that full solutioning and subsequent aging may not have been achieved throughout the casting due to the mass of material which prevented a rapid quench. Yield strength (0.2% offset) approached the ultimate tensile strengths. Elongations were quite low averaging only 4%, a figure approximating elongations of thin test section specimens from stylized castings. The chordal elongations are higher due in part to measurement over a 0.6 in. length instead of the usual 1 in. The chordal specimens do show that the quench was more thorough near the impeller circumference due to the smaller mass in that area. It had been intended to generate specimens from the shaft area but examination of a 2-inch diameter section showed a void which precluded specimen preparation. Radiographic examination of the tensile specimens showed only weak sporadic indications, none of which was associated with the tensile fractures. Chordal specimen strength data showed good correlation with data from the heavy sections of stylized specimens, i.e., 156 ksi ultimate strength for the impeller vs 155 ksi for the stylized casting.

3.2.4 Metallographic Evaluation - Impeller Casting

Basic microstructure of the impeller casting (STA) were essentially identical to those observed in stylized castings (STA) with respect to grain boundry and matrix characteristics. Grain size was rated in the same manner as described in Phase 1, paragraph 3.1. Grain size in the base plate area, from which chordal tensile specimens were generated, was approximately 7-1/2 -9 as compared to 1-3 and 8 for the thick and thin sections of the stylized castings.

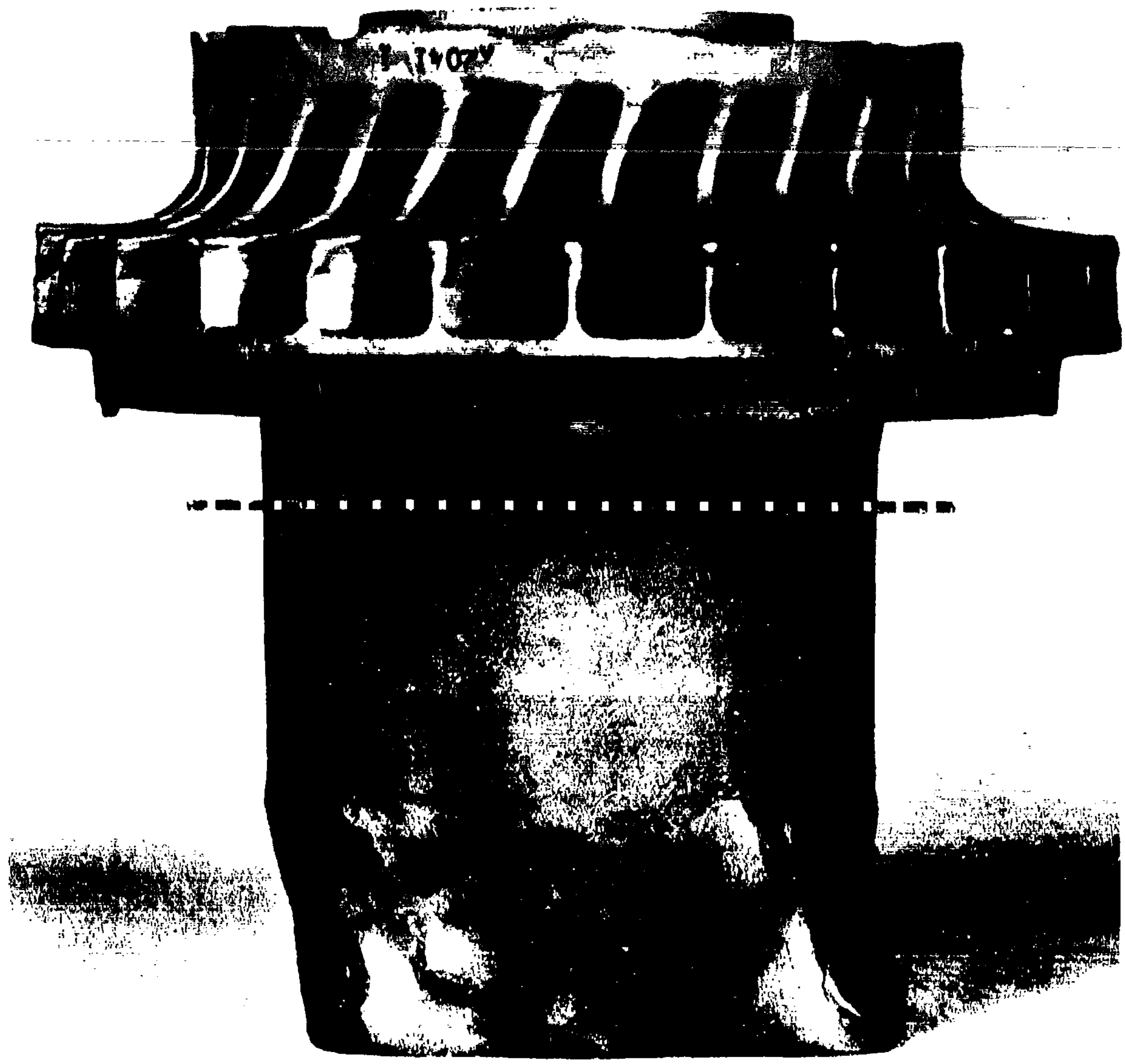


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Figure 26. As-cast Ti-6Al-4V alloy impeller. Casting was sectioned along dotted line prior to heat treatment and subsequent preparation of tensile specimens. (Magn 100X)

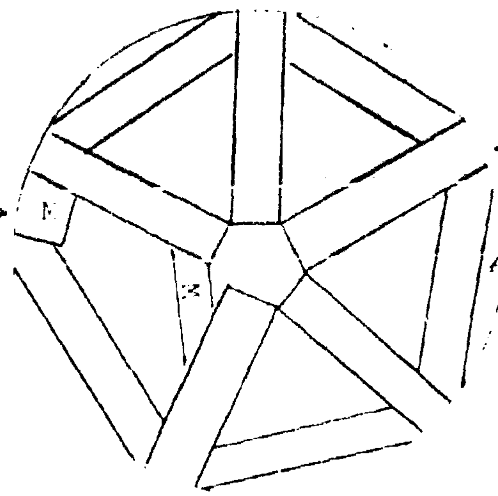

Figure 27. Sketch showing location of tensile and metallographic specimens from Ti-6Al-4V skull melt impeller casting.

3.2.5 Spin Testing

One impeller casting was procured for spin testing. Fluorescent penetrant inspection (FPI) of the casting, in the as received condition, revealed cracks in several airfoils, some of which were through cracks as long as 0.5 in. In addition, several small cracks were noted in the surface of the hub between the roots of airfoils. Typical FPI indications are shown in Figures 28 and 29. A few of the airfoil cracks increased in length during subsequent solution treatment but no growth occurred during aging.

Visual examination revealed some minor surface pitting on the outside diameter of the hub between the airfoils. This condition probably was a result of microcrazing of the tungsten face coating of the shell mold related to disparity in the curing cycle of ceramic shell material in these extremely tight blind recesses.

Prior to heat treatment, a large portion of the heavy gating was removed to insure an adequate quenching rate in the hub area. The casting was solution treated at 1750F - 1 hr (Argon) + H_2O quench and aged at 1000F - 4 hrs (Air) + A/C.

This impeller was cast from a different heat of material than had been used to produce the stylized casting and the first impeller casting that was used to generated mechanical property data. The casting supplier suggested that a lower solution temperature might have been beneficial from the fracture toughness standpoint.

Table XVII

Room Temperature Tensile Properties of Specimens Generated from Ti-6Al-4V Impeller Cast by the Skull Melting Process

Location	UTS, ksi	0.2% YS, ksi	Elongation, %	Modulus of Elasticity 10^6 psi	Note
Radial	144.2	140.5	2.2	15.8	Elongation Measured in/in
Radial	148.9	145.8	5.0	13.8	
Radial	146.0	140.5	5.3	Not measured	
Radial	147.4	146.7	3.5	Not measured	
Radial	144.0	131.0	4.2	Not measured	
Avg.	146.1	140.9	4.0	14.8	
Chordal	157.3	---	13.1	Not measured	Elongation Measured in 0.6 in.
Chordal	151.9	146.3	9.8	Not measured	
Chordal	156.0	155.0	8.0	Not measured	
Chordal	153.0	144.0	8.1	15.9	
Chordal	161.0	151.0	11.3	16.0	
Avg.	155.8	149.1	10.0	15.9	

Heat Treatment:

Solution: 1750F-1 hr in argon - H_2O quench
Age: 1000F-4 hrs - air cool

Preliminary evaluation of the deficiencies noted in the casting suggested that the condition of the impeller was marginal relative to spin testing. However, it was considered appropriate to conduct the spin test as programmed. The appearance of the impeller as finish machined for spin testing is shown in Figure 30.

The impeller was spin tested at room temperature. The procedure consisted of spinning at 30,000 rpm for 0.5 min and then increasing the speed in increments of 6,000 rpm, holding for 0.5 min at each step. Failure occurred at 50,000 rpm in the airfoils. An overall view of the failed impeller is shown in Figure 31. The exact origin of failure could not be determined. However, the failure path included portions of at least two pre-existing cracks, one of which was a through crack approximately 1.0 in long, as evidenced by the heat tinted surface shown in Figure 32. The aforementioned deficiencies in the outside diameter surface of the hub were not involved in the failure. The failure rpm was only half of the predicted burst rpm.

It was predicted that burst of this impeller would occur near 100,000 rpm. This prediction was based on the following criteria:

- Blades and hub were to print.
- Elongation was in excess of 5%.
- There were no flaws of critical size such that fracture toughness became the basis on which to predict burst.
- Failure would be based on ultimate strength.

The calculations utilized the following mechanical properties which were determined earlier in the program.

Ultimate strength - 150,000 psi
Elongation - 6%
Density - 0.160 lbs per cu in

The prediction was based on calculations that utilized pre-existing data obtained from steel impellers of the same configuration, making the necessary adjustments for density differences. Utilization factors (average tangential stress/ultimate tensile stress) of 0.75 and 1.0 were employed in the hub and airfoil stress analyses, respectively. Because of the difference in utilization factors the predicted burst speeds based on both the hub and airfoil analyses, were essentially the same.

It was calculated that, at failure, the average tangential stress of the hub reached 25,000 psi with maximum stresses as high as 70,000 psi at the bore. The airfoil experienced maximum stresses of approximately 32,000 psi. It was, therefore, concluded that the defects in the airfoil were of such a magnitude that the structure was unable to realize its inherent ultimate strength capability.

Post spin tensile tests were conducted on chordal specimens taken from the web of the impeller, as illustrated in Figure 27. The average results are as follows:

Ultimate strength	- 160,000 psi
0.2% Yield strength	- 155,000 psi
Elongation in 1 inch	- 4.0%

The strengths are slightly higher and the elongation slightly lower than determined earlier in the program. These differences in data suggest slightly lower fracture toughness than anticipated prior to spin testing. This condition simply amplifies the influence of the aforementioned airfoil defects.

It appears that the state of the titanium casting art in existence at the time the impeller was cast was not adequate to produce an unusually complicated impeller shape capable of demonstrating full realization of its mechanical properties in a high speed rotating application. However, the casting supplier has manufactured somewhat simpler impeller shapes which have performed satisfactorily in high speed rotating applications.

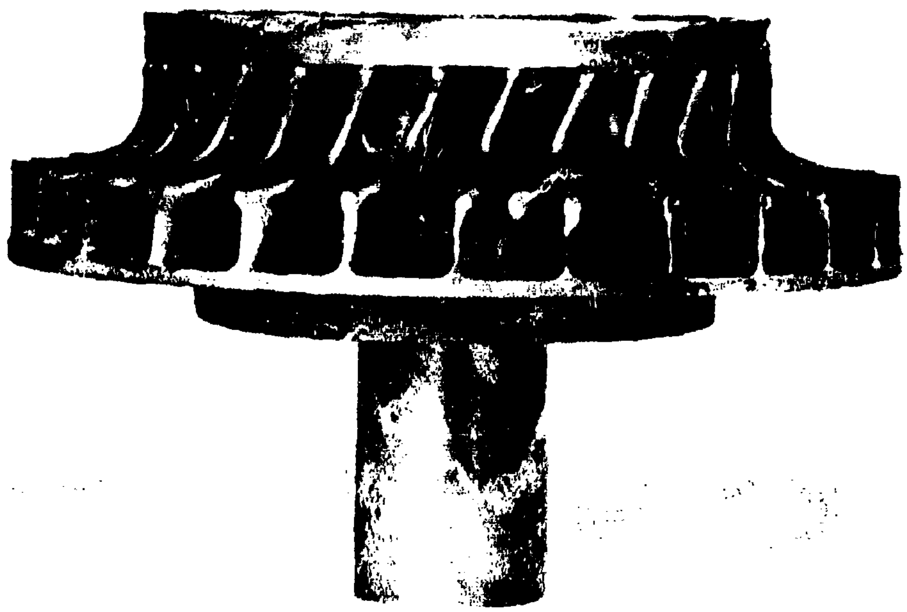

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Figure 28. Ti-6Al-4V cast impeller showing FPI indications.

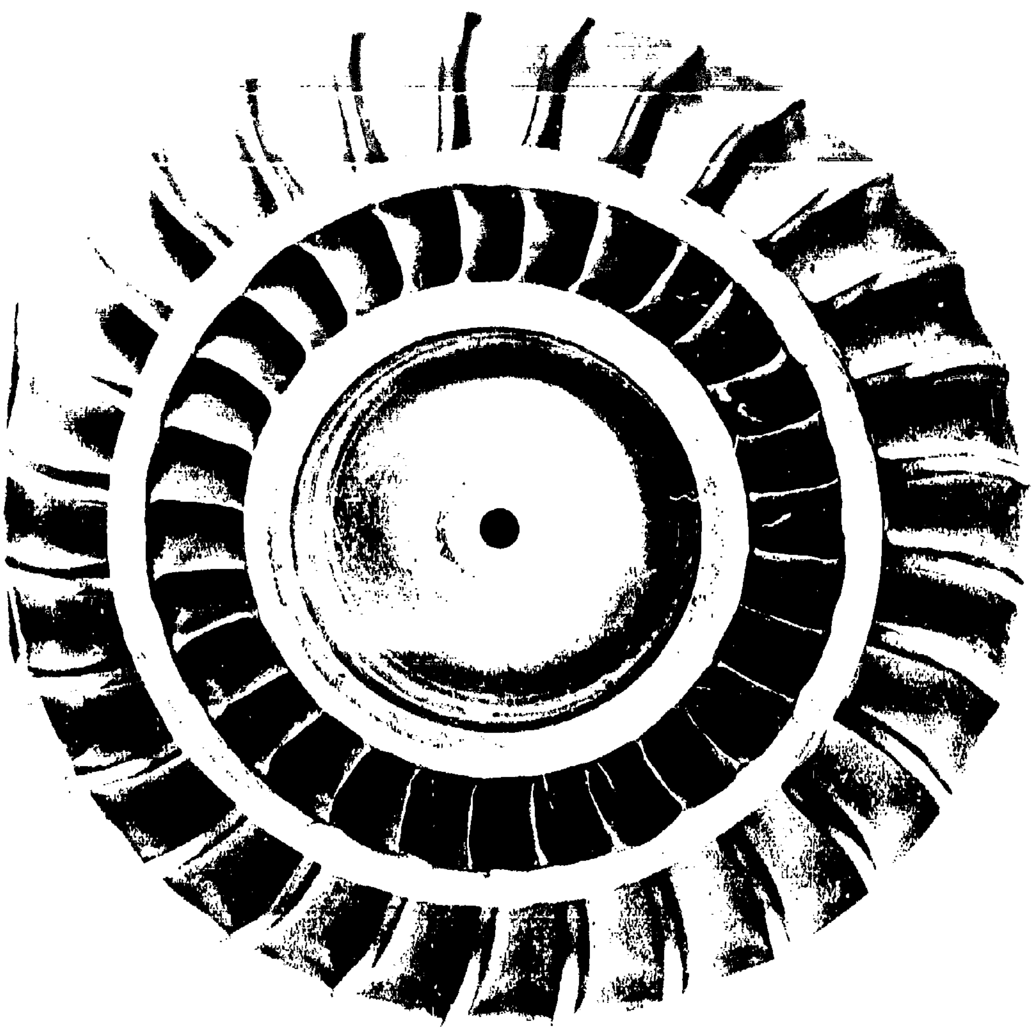

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Figure 29. Ti-6Al-4V cast impeller showing FPI indications in the airfoils.

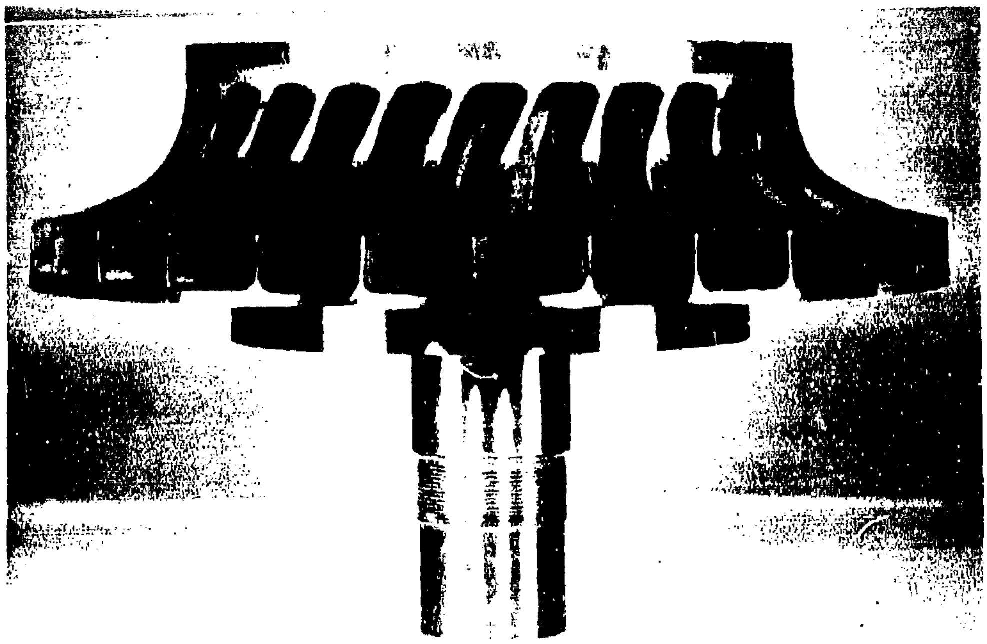

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Figure 30. Ti-6Al-4V cast impeller finish machined for spin testing; cast by REM Metals Corp.

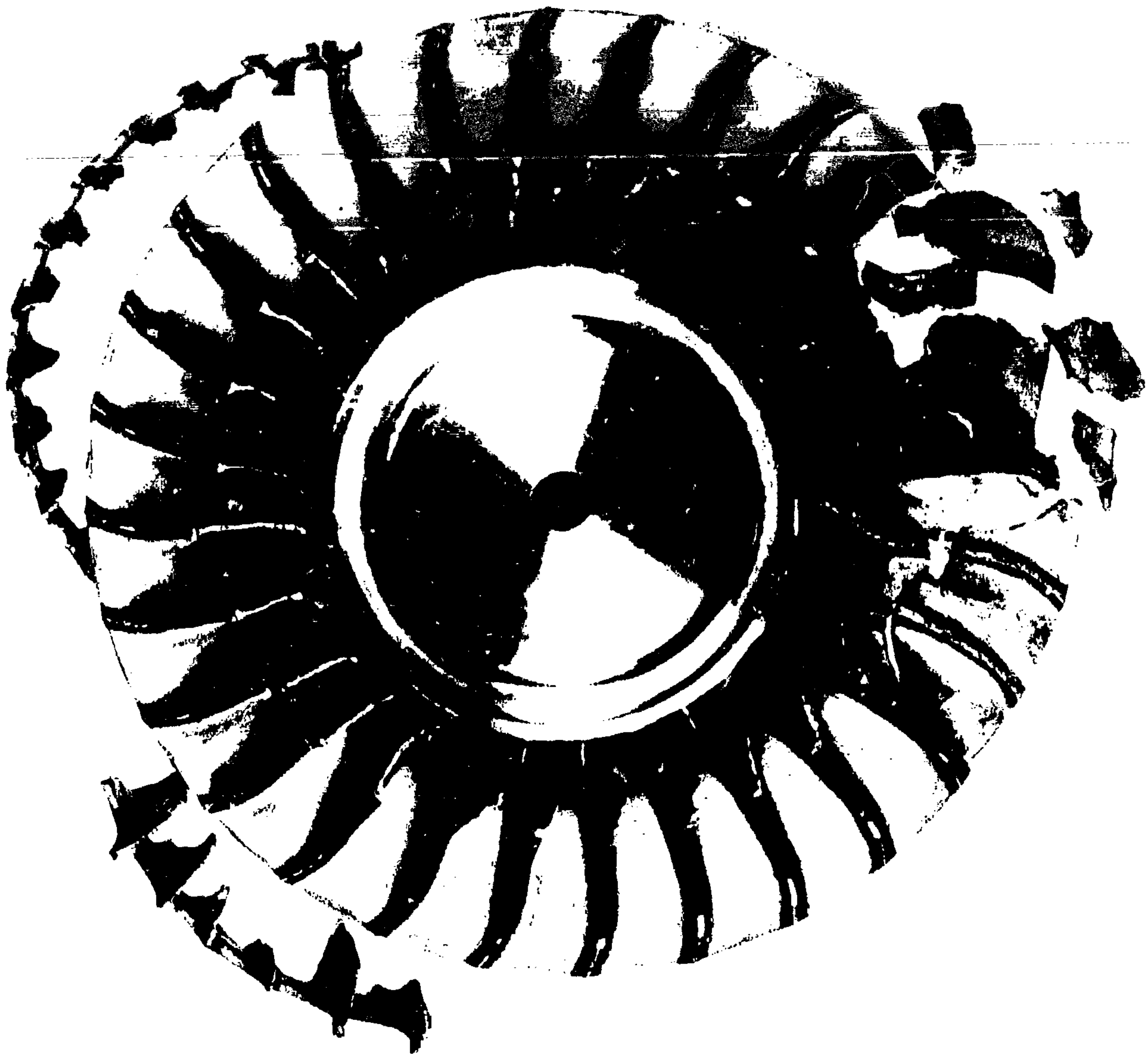

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Figure 31. Overall view of a cast Ti-6Al-4V impeller after spin test.

Magn 5X. Neg. No. 8-33555

Figure 32. Fractured airfoil showing heat tinted area, indicative of crack existing prior to heat treatment.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

There is no apparent need to develop new titanium alloys for the purpose of producing complex cast shapes.

The castability of Ti-6Al-4V, 5621S, IMI700 and Beta III alloys is essentially the same and is sufficient to permit casting of complex shapes with high aspect ratio thin sections.

A slight taper of 1-3 degrees is required to achieve high levels of internal soundness, e.g., ASTM E192, Grade 3 or better, in thin cast titanium sections, e.g., 0.060-0.080 in., with aspect ratios of $\sim$ 20:1.

Contamination of cast titanium surfaces related to mold reaction can be avoided by use of refractory metal face coated ceramic shell molds.

The skull melting process is more amenable than the bottom pour induction melting process to production of complex titanium alloy castings with high aspect ratio thin sections which require high levels of internal soundness.

Induction melting has considerable promise as a means for producing titanium castings of relatively simpler configurations than those involved in this program.

Of the cast alloys investigated, Ti-6Al-4V offers a combination of mechanical properties compatible with requirements cited by designers of advanced gas turbine engine rotating components such as a compressor impeller.

Instrumentation of ceramic shell molds to record solidification and subsequent cooling curves is not a useful tool for optimizing or monitoring titanium alloy casting practices.

Castings of Ti-6Al-4V, 5621S and Beta III alloys have excellent resistance to damage from impact by high velocity foreign objects. IMI700 alloy is relatively susceptible to ballistic impact damage.

Uniaxial tensile ultimate and 0.2% yield strengths of appropriately heat treated Ti-6Al-4V, 5621S, IMI700 and Beta III alloy castings are essentially equal in heavy and thin sections and to strengths exhibited by these alloys in wrought form. Tensile ductility is somewhat lower in the cast form.

700F cast and wrought LCF lives for Ti-6Al-4V alloy are essentially the same for strain ranges less than 10%. No room temperature wrought data were available for comparison.

The 5×10^6 cycle endurance limit of cast Ti-6Al-4V alloy is comparable to that of the alloy in wrought form. The endurance limit to ultimate tensile strength ratio for cast 5621S and Beta III alloys is considerably less than exhibited by cast Ti-6Al-4V.

Additional studies should be conducted to determine whether mechanical properties of titanium alloy castings can be enhanced through the use of unique thermal treatments.

Induction melting should be further evaluated to determine the range of applications and economic advantages which could be derived from this casting method.

The state of the titanium casting art in existence at the time the unusually complicated impeller shape evaluated in this program was cast was not adequate to produce an impeller capable of demonstrating full realization of its mechanical properties in a high speed rotating application.